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AGRICULTURAL UTILIZATION OF
MUNICIPAL ANIMAL AND
INDUSTRIAL WASTES

**United States
Department of
Agriculture**



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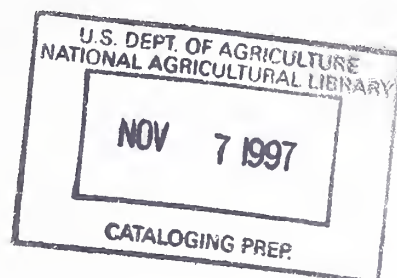
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Agricultural Utilization of Municipal, Animal and Industrial Wastes

United States Department of Agriculture

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Preface

America's cities, farms and industries are producing increasing amounts of wastes. Sewage sludge and solid wastes from our cities, animal manures from our farms and coal combustion residues and other by-products from industries require environmentally safe and cost-effective methods of disposal. The waste utilization problem presents a challenge and an opportunity for U.S. agriculture. Animal wastes as well as many municipal and industrial wastes may have substantial value if properly used in agriculture. Development of methods to optimally integrate waste into agricultural practices could improve the sustainability of agriculture and provide solutions to waste disposal problems.

This report focuses on major waste sources that have potential for agricultural utilization including municipal wastes (sewage sludge and solid waste), industrial wastes (coal combustion residues and other selected by-products) and agricultural wastes (animal manures). Individual chapters on each major waste source provide information on amounts produced, composition of the waste, current uses, state of knowledge relative to land application, problems and opportunities associated with agricultural/horticultural uses of the waste and research needs. The final chapter provides a summary of the issues involved in agricultural utilization of wastes and characterizes the research needed to transform a waste disposal problem into an environmentally safe agricultural resource.

DRAFT

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Executive Summary

America's cities, farms and industries are generating in excess of 910 million Mg (one billion tons) of wastes per year. Most of the 182 million Mg (200 million tons) of municipal wastes produced annually is placed in landfills, but landfill capacity is decreasing. New environmentally safe landfills which meet USEPA standards are costly and tipping fees are expected to exceed \$110 per Mg(\$100 per ton) in certain areas of the country by the year 2000. Many of our urban areas have an urgent need for long-term environmentally safe methods for recycling and disposal of wastes. Our industries produce hundreds of millions of tons of wastes or by-products annually. Alternative uses have been found for a small fraction of these materials, but most by-products are stockpiled at the site of generation or are taken to landfills. Most of our meat and dairy products are produced by large cost effective operations where livestock and poultry in confinement generate hundreds of millions of tons of manure annually. Accumulation of large amounts of animal, municipal and industrial wastes at the production site can result in degradation of soil, water and air quality. Components of the wastes and their degradation products can cause odor problems, greenhouse effect gases such as carbon dioxide and methane can be released to the atmosphere and nutrients, trace elements and micro-

organisms can contaminate surface and ground water. Agronomic management practices to protect environmental quality at the production site and to effectively utilize wastes in agricultural production systems are urgently needed.

Waste utilization problems present a challenge and an opportunity for U.S. agriculture. We are currently confronted with the long-term goal of developing crop production practices that promote sustainability. Animal wastes and many municipal and industrial wastes have substantial potential value for agricultural utilization. Many of the wastes contain essential nutrients that could meet crop requirements if applied to our land in the proper manner at the right time and in suitable amounts. Utilization of nutrients from wastes could reduce dependence on fertilizers from our limited supply of mineral resources and thereby increase the sustainability of our agricultural systems. Organic wastes can serve a valuable role as soil conditioners and as a means of enhancing soil organic matter levels which tend to decline with cultivation. Wastes or mixtures of wastes may also find specialty uses in the horticultural industry. The development of methods to optimally integrate waste utilization into sustainable agricultural practices could provide a major part of the solution to urban and industrial waste disposal problems.

Investment in research and education will be needed to increase and improve agricultural utilization of municipal, industrial and animal wastes. Additional research in the following areas will ensure efficient and environmentally safe utilization of a variety of readily available waste materials.

1. A national data base listing the amounts produced and the agronomic characteristics of major municipal, animal and industrial wastes is needed. A range of values for agronomically important parameters such as pH, nutrients and toxic trace elements will facilitate selection of wastes that will benefit the soil-plant system and identify wastes whose application should be restricted.

2. Analytical methods are needed to estimate the levels of nutrients and toxic components in wastes and soils amended with wastes. This information will allow selection of waste application rates that will keep nutrient levels within beneficial ranges, avoid contamination of our waters and facilitate loading rates that are cost effective and timely.

3. A careful assessment of the fate and effects of trace elements, synthetic organics and pathogens in wastes on soils, plants, animals and humans must be made. A risk assessment pathway approach similar to that used to develop regulations for land application of sewage sludge will be needed for other wastes. This information will be necessary to address public concerns and to develop appropriate

regulations for land application of waste materials.

4. Research is needed to minimize loss of nutrients from wastes during storage, handling and field application. Approximately 75% of the nitrogen in animal wastes is lost before it is available for crop use. An understanding of basic chemical and biological processes in wastes and waste mixtures will allow systems to be designed for environmentally safe storage of wastes until times when they can be beneficially applied to land.

5. Methods of incorporation and surface application of organic wastes (including irrigation) should be evaluated to develop methods to minimize losses of objectionable gases and bioaerosols, disease transmission and potential for runoff and contamination of surface waters by nutrients, trace elements and microorganisms. Benefits associated with enhanced soil organic matter levels would include: protection from erosion, increased water infiltration rates, higher available water holding capacity, increased plant rooting depth and enhanced supply of nutrients.

6. Research is needed to determine the chemical behavior of waste materials in soils. This is particularly true of new technology coal combustion wastes such as flue gas desulfurization products which contain high amounts of calcium sulfite. Research is needed to determine favorable conditions for rapid oxidation of sulfite to sulfate

in soils to avoid potential plant growth limitations.

7. An understanding is needed of the influence of factors such as aeration, temperature, water content, inoculation and mixing on populations of pathogens, beneficial organisms and viable weed seeds in wastes, waste mixtures, composts and soils. This information will be used to develop guidelines for specialized uses of wastes such as controlling pathogens, biologically mediating nutrient uptake and enhancing populations of beneficial organisms in soils and other plant growth media.

8. Research is needed to blend, mix or co-compost different wastes to produce final products with desirable characteristics for agricultural or horticultural uses. Information on the concentrations, chemical reactions and bioavailability of beneficial and potentially hazardous components of wastes will be needed to develop mixing and composting procedures which can eliminate pathogens and toxins, reduce availability of toxic trace elements and enhance nutrient availability in "designer waste" end products.

9. Regulations that protect the environment and human health while allowing utilization of beneficial materials must be developed and uniformly applied by regulatory agencies to increase agricultural utilization of wastes. Regulations developed using a risk assessment approach will help overcome current barriers to agricultural utiliza-

tion of wastes posed by state regulations that are excessively restrictive and may not have a sound scientific basis.

As the real advantages associated with careful agricultural utilization of wastes are determined and hazards are defined and controlled, efforts will be needed to convey this information to the agricultural community and the public. Successful handling of the waste disposal problem will require a partnership between the urban and agricultural sectors. The agricultural sector will need to know which waste materials can be land applied, how much can be applied and what are environmentally safe methods of application. The public will need to be convinced that agricultural utilization of wastes is environmentally safe, cost effective and does not pose a human health risk. Waste producers and the public may have to pay additional fees to make waste utilization more attractive to farmers. Waste transportation expenses may have to be subsidized and additional steps taken at the waste production site to produce a more valuable product for agricultural and horticultural uses. These expenditures, however, may be small compared to increasing costs of current waste management practices and benefits to be gained through environmentally safe utilization of wastes in agricultural operations.

Agricultural Utilization of Municipal Wastes

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Agricultural Utilization of Municipal Wastes

Summary

Environmentally and economically sound, recycling and reuse programs are logically appealing to municipalities confronted with waste disposal limitations. Conceptually, the general public via legislative decisions has recognized and acted on the need to reduce costs and reclaim wastes by treating them as resources. As with natural resources, such as water, soil, air, and minerals, preservation of the balance in nature requires careful management which considers impacts of treatments and uses. One of the major problems confronting waste managers is the sociopolitical issue associated with siting and operation of resource recovery (waste reclamation) facilities. Justifiably, the public in each jurisdiction considering waste management alternatives requests information on the environmental impact of such facilities and their products. Often, however, the questions raised cannot be answered presently because of a significant gap in information or because there has been a hiatus of major research effort at the federal and state levels for nearly 12 years.

With specific regard to composting it has recently been noted that: "Because governmental guidance on composting has been either faulty or nonexistent, those concerned with waste management have found it dif-

ficult to assess composting's role as an essential element of needed waste management infrastructure. Composting system vendors, industry-driven lobbying organizations, and trade and other publications, appointing themselves authorities in the field, have refused to fill the information void. The result has been misinformation and confusion on composting process design and vested-interest-driven decisions on compost product utilization" (Maz-zocchi, 1992, p.1).

In 1980, Sanderson noted that "economics is the greatest deterrent to sewage-refuse compost use. It is simply cheaper to bury, burn or dump our wastes." In 1993, municipalities and their citizenry are confronted with the rapidly increasing cost of waste management and the urgent need to protect the quality of the environment for posterity. At this same time, agriculture is confronted with the urgent need to use crop production practices that promote sustainability, also a long-term concern. The needs of the agricultural sector and the urban sector are serendipitously compatible. The task for agriculture is to determine how much and which waste-resource materials can safely and economically be applied to land or agricultural

(horticultural) production systems and in what manner.

Current U.S. production of municipal solid waste (MSW) approaches 182 million Mg (200 million tons) per year; sewage sludge production approaches 7.3 million Mg (8 million tons) per year. Approximately 57% (114 million tons) of MSW is organic and recyclable with an average NPK value of 0.7-0.2-0.3. Thus, the fertilizer equivalency value is about \$378 million to U.S. farmers. For sewage sludge with an average NPK value of 4-2-0.4, the value to U.S. farmers is about \$72 million in the first year of land application. In addition to this first-year value, land application of MSW and SS has long-term economic and agronomic value which derives from the synergistic effects of increased organic matter on plant nutrient uptake and on improvements in soil quality and productivity. Also, agricultural use of MSW and SS has benefit to society as a whole by reducing or eliminating the high economic and environmental costs of alternative disposal methods including incineration and landfilling.

Municipal wastes which typically are highly cellulosic, have relatively low plant nutrient value; untreated sewage sludge is nutritionally similar to animal manure. Treatments such as composting and digestion reduce the N and K content and increase the P content of sludge. The fertilizer value of wastes

depends on the elemental and organic matter content, mineralization rates, and carbon: nitrogen: phosphorus ratios. The value of these wastes resides to a considerable extent not in their inherent fertilizing values but in their organic matter content which interacts synergistically with elemental nutrients in soil to improve the effective fertilizer value and physical properties of the recipient soil.

Grinding or composting improves the particle size uniformity and distribution so that wastes can be applied to soil surfaces as a mulch, applied in furrows, troughs or trenches or incorporated by tillage. Liquids and semisolids can be sprayed uniformly.

Improvements in the agronomic uses of treated and untreated MSW and SS depend on research and development on the following topics:

1. Heterogeneity and range in chemical and physical characteristics of the components in the wastes;
2. Combinations of mineral fertilizers and wastes to secure environmentally, agronomically, and economically acceptable uses;
3. Evaluation of the benefits of the organic constituents in MSW and SS in improving soil physical-chemical properties;

4. Techniques, mixing ratios, benefits and uses of mixtures of agricultural and municipal wastes.

5. Blending of organic and industrial wastes to provide products that are tailored to specific applications while reducing the bioavailability of metal and organic contaminants carried in some wastes.

Horticultural uses of MSW and SS primarily require composting of these materials to provide a stabilized, nonphytotoxic product that is easy to store and handle. Of the organic materials currently used in potting media (peat and pine bark) at least 40 percent could be supplied from other sources such as composted MSW and SS. Properly managed compost can reduce the need for fertilizer and fungicide, and in turn reduce contaminants in leachate.

Improvements in the horticultural use of composted MSW and SS depend on research and development on the following topics:

1. Quality and maturity tests and criteria applicable to composts produced from a variety of feedstocks;

2. Process technology for co-composting SS and MSW;

3. Reliable enhancement of microbially-mediated plant disease suppression in composts;

4. Reliable inoculation methods for beneficial root microorganisms that assist plant uptake of nutrients and thereby reduce dependence on inorganic fertilizers.

The potential barriers and constraints to adoption of agricultural uses of composted MSW and SS include the public perceptions and information about odor management, pathogen destruction, water quality impacts, and bioavailability, phytotoxicity, and risk assessment associated with metals and organic compounds. Another constraint involves the need to thoroughly mix the various feedstocks to achieve successful composting. Successful compost process management requires consistent and careful operator attention during all phases of the process. This requires real-time process management decisions and actions to preserve adequate heating and aeration of the product.

Farms can be the site for composting some wastes, especially leaves, food processing wastes, and other organic materials. Limitations to on-farm composting center on transportation, local regulations, presence of contaminants, on-farm costs, farmer education, and reliable transfer of the wastes from urban collection to on-farm composting centers. On-farm composting and co-composting will require development of 1) ways to adequately compensate farmers for the services they perform, 2) a coordinating entity that will facilitate movement of wastes

between farmers and municipalities, and 3) revision of government guidelines to include co-composting of municipal and farm wastes and to acknowledge the environmental differences between farm and urban composting facilities.

The necessity to recycle that portion of wastes which is safe and beneficial and the value of such wastes in the agricultural and horticultural industries leads to a potential partnership between urban and rural communities. The likelihood for success is based on past research accomplishments but new research with the goal of direct technology transfer for immediate implementation must be initiated for this partnership to succeed. Identification of suitable wastes, treatment of these wastes for optimum benefit and utilization in an environmentally safe manner are achievable research goals.

A. Introduction

In the United States, the traditional waste management practices used for sewage sludge and municipal solid waste are now recognized as increasingly environmentally, ecologically, and economically inadequate. As a nation we are generating waste than ever before, and many areas are quickly exhausting their standard options for safe, effective management of wastes. Regulatory guidelines and limits to traditional waste management practices also are being implemented at national, state, and local levels. Thus, while the handling capacity diminishes because landfills and incinerators continue to close, the production of wastes increases, but it is increasingly difficult to establish new disposal facilities.

Communities face hard choices when evaluating waste management options. New York City, for example, has paid premium prices to transport wastes long distances to sites willing to accept and utilize them. Other communities have encountered intense public conflict when siting disposal facilities near the waste collection sites. Not all communities face such problems, however. Some have found creative solutions through source reduction and recycling programs, and have been able to site new, environmentally acceptable disposal facilities. Still, for much of the nation, innovative solutions for waste management are much needed.

Component identification in a waste stream is an essential step in addressing the problems associated with their generation and management. Municipal solid waste (MSW) characterizations involve estimations of how much is generated, recycled, incinerated, and disposed of in landfills. The data are used to establish waste management goals and plans at the national, state and local levels. For example, waste characterization can reveal opportunities for source reduction and recycling and provide data on special management issues.

B. Quantities and Management of Municipal Solid Wastes and Sewage Sludge

Municipal Solid Wastes (MSW)

In 1990, 177.7 million Mg (195.7 million tons) of MSW were generated in the U.S. This is equivalent to 1.95 kg (4.3 pounds) per person per day. After materials recovery for recycling and composting, discards were 1.63 kg (3.6 pounds) per person per day. Virtually all of these discards were incinerated or landfilled. It is estimated that by the year 2000, waste will accumulate at 202 million Mg (222 million tons) per yr. (4.5 lbs/person/day), unless source reduction is implemented.

Both volume and weight of MSW are used to evaluate the scope of the recycling problem; volume is used to estimate how quickly landfills will reach capacity and the rate of change of various materials in the waste stream. A breakdown of the 1990 MSW by weight and volume is shown in Table 1. Paper and paperboard products are the largest component of municipal solid waste by weight (37 percent) and by volume (32 percent). Yard trimmings are the second largest component (18 percent, by weight). Glass, metals, plastics, wood and food wastes range from 6 to 9 percent each by weight of total MSW. Rubber, leather, textiles, and small amounts of miscellaneous wastes comprised less than 4 percent each of MSW. Paper and plastics combined accounted for over one-half of the volume of MSW discarded in 1990. The three major methods for MSW disposal in 1990 were landfilling, recovery for recycling, and incineration, with 118,30 and 21 million Mg per method, respectively (USEPA, 1990b). The composition indicates that 70-80 percent of the waste stream is combustible, recyclable, and/or compostable (Clarke, 1992).

Sewage Sludge (SS)

Recently the U.S. Environmental Protection Agency (USEPA, 1990a) estimated that about 7.7 million Mg, i.e., 64 lbs. per capita, of sewage sludge were generated in the U.S. annually; the projection for the year 2000 was 15.4 Mg (USEPA, 1989a). With the expected population growth, technological improvements in sewage treatment plant operations, federal restrictions on ocean dumping, and the 40 CFR 503 rules for land appli-

cation of sludges containing high concentrations of metals and toxic organic chemicals (USEPA, 1993), sludge production and concurrent disposal needs will also increase. Landfills in the U.S. simply will not accommodate the expected high volume inputs from this single source (USEPA, 1990a). Unless the U. S. develops and implements the necessary technology to reduce its heavy reliance on landfilling and incineration the nation will not meet the USEPA's outlined goals and objectives for improving environmental (soil, water and air) quality (USEPA, 1989b). Equally significant to these goals is the urgent

Table 1. Weight, Volume and Recovery of Municipal Solid Waste (MSW)^a Materials in 1990.

Material	Weight generated (million Mg)	Weight recovered (million Mg)	Percent recovered of material generated	Material discarded (million Mg)	Weight of MSW (% of Total)	Volume of MSW (% of Total)	Ratio ^b vol % weight %
Paper and paperboard	66.6	19.0	28.6	47.6	37.5	31.9	0.9
Glass	12.0	2.4	19.9	9.6	6.7	2.2	0.3
Metals							
ferrous	11.2	1.7	15.4	9.4	6.3	8.9	1.4
aluminum	2.5	0.9	38.1	1.5	1.4	2.2	1.6
other non-ferrous	1.5	0.7	67.7				
Plastics	14.7	0.4	2.2	14.4	8.3	21.1	2.5
Rubber and leather	4.2	0.2	4.4	4.0	2.4	6.1	2.5
Textiles	5.1	0.2	4.3	4.8	2.9	6.4	2.2
Wood	11.2	0.4	3.2	10.8	6.3	6.8	1.0
Food wastes	12.0	neg.	neg.	12.0	6.7	3.2	0.5
Yard trimmings	31.8	3.8	12.0	28.0	17.9	9.8	0.5
Miscellaneous inorganic wastes	2.6	neg.	neg.	1.4			
Other	2.9	0.7	23.8	5.2	1.6	1.4	0.4
Totals	177.7	30.3	17.1%	147.4	100%	100%	1.0

^a MSW includes durable goods, nondurable goods, containers and packaging, food scraps, yard trimmings and miscellaneous inorganic wastes from residential, institutional and industrial sources. Wastes include appliances, newspapers, clothing, boxes, disposable tableware, office and classroom paper, wood pallets, and cafeteria wastes. Specifically excludes from MSW are construction and demolition materials, municipal sludge, combustion ash and industrial process wastes.

^b Ratios greater than 1.0 indicate that the materials are less dense and occupy a greater proportion of landfill space by volume than by weight; the converse is true for materials with ratios of 0.5 or less.

need to implement programs based on the sustainable growth and development vision which involves all sectors of the nation's economy. One of the clearly critical elements of this vision requires development of economic recovery methods and appropriate use of resources that are available through recycling. Our national obligation to conserve and protect our natural resources would be well served through the realization of the opportunities for safe and beneficial use of sewage sludge.

C. Utilization of Treated And Untreated Wastes.

Strategies for Improved Management And Utilization Of Municipal Wastes

The national recycling goal, which encompasses resource recovery, reuse, recycling, and reduction of landfill volume (USEPA, 1989c), cited the recycling of solid waste at a 25 percent increase by 1992. Parr and Hornick (1992) estimated that meeting this goal should result in a 55 percent decrease in the landfilling of solid waste, with a 20 percent increase in incineration. To achieve this goal, some municipalities have begun implementing source separation and collection programs to support the recycling of paper, metals, glass and plastics, and to specify the collection/composting of bulky yard wastes. Jurisdictional prohibitions against landfilling of yard wastes (Pelzer, 1990) have resulted in municipally operated or contracted waste collection and composting which produce compost that is used in a wide variety of horticultural and landscape situations. In addition, some localities have encouraged backyard composting especially of yard wastes and have sought guidance from private foundations experienced with the variety of small-scale techniques available (Roddale, 1982).

Composting

Composting is a time-honored farming practice used for converting organic wastes into useful soil conditioners and biofertilizers. It is increasingly viewed as a viable and important means of stabilizing and transforming municipal wastes so that they can be used safely and beneficially in agricultural, horticultural, and forestry operations (Parr and Hornick, 1992; USEPA, 1989a; USEPA, 1989b; USEPA, 1989c; U.S. House of Representatives, 1990). Several of the problems (e.g., malodors, human pathogens, and undesirable chemical and physical properties) which occur when raw and unstable organic wastes are directly applied to soil as amendments can be resolved by composting.

Composting is commonly regarded as a microbiological process that accelerates the decomposition of organic materials through the growth, activity, and heat production of mixed populations of bacteria and fungi that are naturally present on the organic wastes (Miller, 1991). Composting can occur aerobically or anaerobically (Gotaas, 1956), but the aerobic mode is preferable because it minimizes the production of malodors, speeds decomposition, and produces high temperatures which are essential for thorough and rapid destruction of pathogens.

The Beltsville Aerated Pile Method was developed to rapidly compost sewage sludge and has been readily adopted by more than 150 U.S. cities and municipalities to manage sludge recycling (Parr, Epstein and Willson, 1978; Parr and Willson, 1980; Willson et al., 1980). Rules (based on cumulative pollutant loading rates) established for the application and use of sewage sludge (composted or uncomposted) on agricultural and non-agricultural land (USEPA, 1993) would also apply to co-composted sewage sludge and mixed MSW, or separated fractions therefrom, according to Parr and Hornick (1992).

D. The Value of Organic Wastes as Biofertilizers and Soil Conditioners.

Parr and Hornick (1992) have delineated the essential factors involved in assessing the "value" of organic waste. They stated that evaluation can be approached in terms of fertilizer equivalency, capacity to alter soil physical properties, and agronomic impact on crop yield and quality. The most direct method of evaluating organic wastes would be to determine the current economic (market) value of the plant nutrients found in the product, especially N, P and K (Table 2). In some cropping situations, the secondary plant nutrient (S, Fe, Mg), micronutrient (Cu, B, Zn, Mn, Mo), and lime equivalency values also need to be assessed. The 'value' of some wastes (as soil conditioners and biofertilizers) could be negative if they contain high amounts of soluble salts, heavy metals, hazardous organic chemicals, or have high C:N ratios or extreme pH values (Parr, Marsh and Kla, 1983).

The benefits to soil physical properties from the added organic fractions of a particular waste may occasionally be of greater economic value than the plant nutrient content. The soil conditioning value of organic wastes is profound for marginal or severely eroded

lands that were reclaimed through the application of composted sewage sludge and feed lot manure (Hornick, 1982; Hornick and Parr, 1987). The economic value (i.e. fertilizer, lime, secondary and micro nutrient equivalency values) of wastes are more easily assessed than the soil conditioning value.

In addition to the nutrient equivalency and soil conditioning values, the agronomic value is used to determine the benefit which results in increased crop yield or quality (Parr and Hornick, 1992). Whereas there is substantial evidence of a positive effect on crop yield, there are very few reliable experimental evaluations detailing the effects on crop quality. The yield response to organic wastes is generally non-linear and at present unpredictable because the interactions and interdependency of crop, soil type, climatic factors, soil and crop management practices, and properties of the waste material are incompletely understood. Crop yields tend to follow the law of diminishing returns; the greatest yields result from application of the first several increments of material, and gradually, the yield increase declines with subsequent additions (Table 2) (Barbarika, et al., 1980; Decker, et al., 1977). Thus, the highest agronomic value per unit of organic material occurs at the lower end of the range of acceptable application rates.

Because the nutrient content of most municipal, industrial or rural organic wastes is

Table 2. Effect of Single Applications of Sewage Sludge Applied to Soil in 1972 and Annual Applications of Chemical Fertilizer on Corn Grain Yields

Sewage sludge ^a Treatment	Corn Grain Yields					Average
	1972	1973	1974	1975	1976	
	100 (kg ha ⁻¹)					
(Dry tons hectare ⁻¹)						
0	25.1	21.1	6.8	16.2	0.91	4.0
56	55.4	68.7	64.6	54.4	38.5	56.3
112	66.5	102.8	68.7	66.0	67.1	74.4
224	61.2	108.4	76.5	69.4	69.2	76.9
N-P-K Fertilizer ^b	34.3	51.0	57.6	50.1	47.7	48.2

^a Sewage sludge was applied at the rates indicated (Mg ha⁻¹, dry weight basis) in 1972 only. No fertilizer was applied other than sewage sludge.

^b Fertilizer plots received 180 kg ha⁻¹ of N, 40 kg ha⁻¹ of P, and 75 kg ha⁻¹ of K each year of the study; no sewage sludge was applied. Source: Barbarika et al., 1980; Decker et al., 1977. (Reprinted from Parr and Hornick, 1992, p.553 by courtesy of Marcel Dekker)

generally low (Parr and Colacicco, 1987; and see Table 2), blending some organic wastes with limited amounts of synthetic fertilizers may be useful to increase the agronomic value of the wastes.

Parr and Hornick (1992) stated that the net profit attributable to the use of organic amendments will depend on the properties of the material, the cost of transportation and application, and the market value of the crop. They further concluded from the work of Barbarika et al. (1980) and Decker et al. (1977) on corn that the financial gain derived from the sustained yield in subsequent crops, (a phenomenon that is linked to the slow release of N and P from the decomposing organic amendments which become mineralized and available for plant uptake and growth) could exceed the financial gain in yield that occurs during the first year (Table 2). For example, Parr and Hornick (1992) calculated the value of sewage sludge to the farmer at \$10.28 per Mg (\$9.33 per ton), based on the fertilizer equivalency values in Table 3 and a corn grain yield of 4800 kg ha⁻¹. They noted that this value would need to be adjusted to account

Table 3. The Value of Some Organic Wastes Based on Their Macronutrient Content

Organic Waste	Nutrients (%)			Value ^a (\$ Mg ⁻¹)
	N	P	K	
Cattle Manure	4.4	1.1	2.4	23.47
Crop Residues	1.1	0.2	2.0	8.44
Sewage Sludge	4.0	2.0	0.4	21.40
Municipal Solid Waste	0.7	0.2	0.3	3.66

^a Value kg⁻¹ of N, P, and K was set at \$0.30, \$0.37, and \$0.20, respectively, based on average dealer prices/FOB of fertilizers at midwest terminal locations, December 1990. Source: Parr and Colacicco, 1987; Parr and Hornick, 1992.; USDA, 1978; (Reprinted from Parr and Hornick, 1992., p. 552 by courtesy of Marcel Dekker)

for the costs of hauling and spreading in certain situations.

Soil productivity is impacted by various factors which may degrade or improve soil properties (Fig. 1). Regular recycling of on-

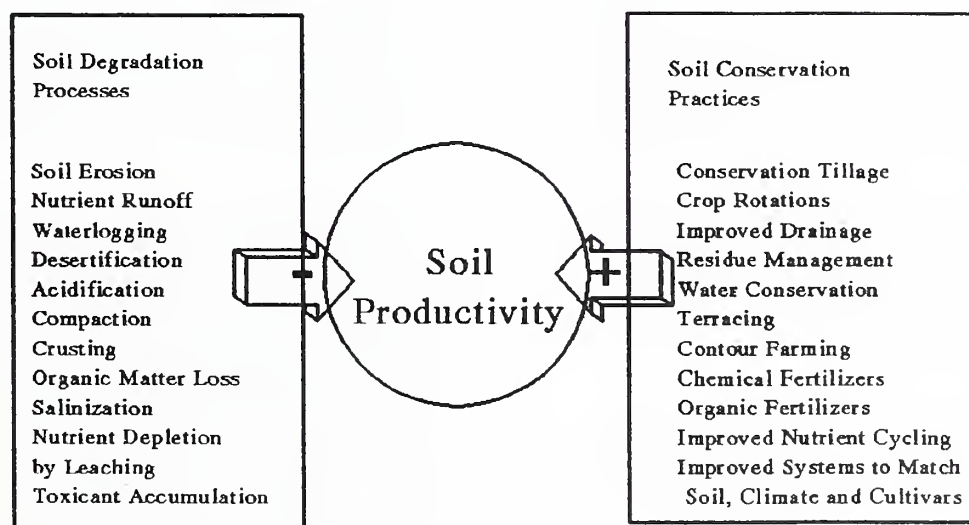


Figure 1. Relationship of Soil Degradative Processes and Soil Conservation Practices to Soil Productivity. (Hornick and Parr, 1987)

farm organic wastes such as animal manures and crop residues will improve the tilth, fertility, and productivity of agricultural soils, protecting them from wind and water erosion, and preventing nutrient losses through runoff and leaching. In some agricultural situations, limited supplies of good quality on-farm organic materials are available to provide adequate soil and water conservation (USDA, 1978). In such cases, composts produced from sewage sludges and biodegradable fractions of MSW could be used to improve soil productivity.

Composted wastes are more stable, easily handled, stored, transported and applied than are non-composted organic wastes. Parr and Hornick (1992) characterized non-composted sewage sludge as an organic material that has a high nutrient availability index (NAI), and that decomposes and mineralizes rapidly in soils. This decomposition releases significant amounts of N and P for plant uptake. In contrast, they characterized composted sewage sludge as an organic material with a high organic stability index (OSI), i.e., a slow rate of decomposition in soil accompanied by a slow rate of nutrient release. In general, the NAI value of an organic material is inversely related to its OSI value. Thus, composted or co-composted sewage sludges and MSW generally can be expected to have a greater inherent value as soil conditioners than as rapidly available source of plant nutrients. They may serve as fertilizer supplements, but not usually as sole nutrient sources.

Parr and Hornick (1992) have noted that a major part of municipal organic wastes could be used beneficially on agricultural lands, especially highly erodible land such as that in the Conservation Reserve Program (CRP). They estimated that about half of the 14 million hectares in CRP that have been set aside and planted primarily with perennial grasses could eventually be returned to crop production, possibly as early as 1996. They proposed that waste application integrated with crop rotation systems be developed to

prevent or stabilize soil movement on such highly erodible lands. Research in support of this use of wastes would be highly beneficial to a vast amount of agricultural soils that are 'at risk' of degradation.

Although the potential for agricultural marketing of composted, co-composted, or uncomposted municipal wastes is very large, access to this enormous market is currently somewhat stalled because the quality of the finished products is unpredictable and occasionally detrimental to plant establishment and growth. Access to the market will require development and adaptation of appropriate technology for reliable production and quality assurance testing of high quality soil conditioners and biofertilizers which can be economically distributed and applied. This goal will require some development of an open and cooperative dialogue between urban and rural communities to solve problems associated with the costs of processing, transporting, and applying municipal wastes. Forecasters (Kashanian et al., 1990; Parr and Hornick, 1992) agree that very large quantities of municipal wastes can and should be utilized on agricultural soils in the future in an effort to improve their productivity and quality. This represents a significant challenge for cooperative interaction among the urban, rural, scientific, and economic communities. Research and solid interpretive analyses are needed to ensure that waste recycling on land is safe, reliable, and beneficial, and economic to both the urban and agricultural sectors.

E. Costs of Collection, Processing, Transport and Application.

Continually increasing production of municipal solid waste in the U.S. and concurrent reduction in the number of landfills in operation, coupled with environmental pressures for a 25 percent reduction in landfilling (Gibson, 1991), have strengthened the need for alternative methods for handling MSW. Costs have skyrocketed, controls have tightened, and technologies are slow and costly to develop. Pressures to meet guidelines imposed by federal and state agencies are compounded

Total MSW

Production in Tons

Data: Glenn, 1992

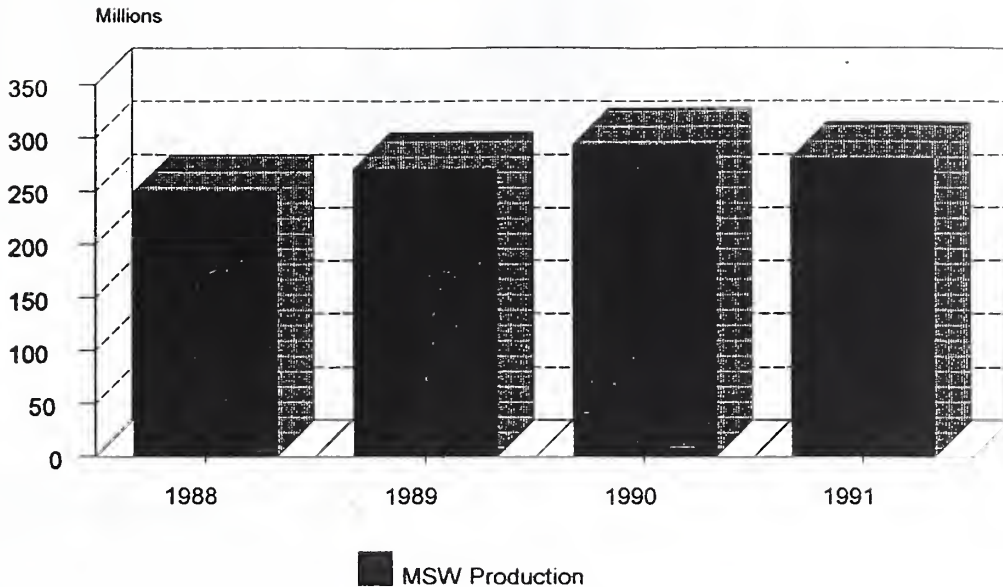


Figure 2: MSW Production.

by increased tipping fees and public opposition to siting. These situations have created an ideal climate for encouraging competitive uses for wastes. Reduction, reuse and recycling are the main avenues for alleviation of the MSW disposal crisis; they are not without problems. Some of these disposal pathways reduce the availability of organic materials directly usable in the agricultural sector.

Size of the Problem.

The lack of a central source of information and referral for reduction/recycling of waste materials causes each jurisdiction to reinvent processes and waste disposal systems or to be led by vendor-driven processing/technology strategies. Municipal solid waste is generated at a rate of about 243-254 million Mg (268-280 million tons) per year (Fig. 2). This figure is significantly higher than those reported by the US EPA, which are based on estimates of per capita rates and the use of es-

timated disposal of wastes by states, not including sewage sludge, yard wastes, and recycling projects (Glenn 1990a). The US EPA estimates that MSW is generated at about 1.8 kg (4 pounds) per person per day (Finstein, 1992).

Disposal Costs

Tipping fees at U.S. landfills have increased to an average of about \$26.50 per ton (Fig. 3), with the more densely populated areas having much higher fees. For example, in the Northeast, the average tipping fee is \$46.83 per ton; Connecticut is the most expensive at \$65.00 per ton. The Rocky Mountain states and the Midwest have the lowest fees.

Compounding the problem of higher tipping fees is a reduction in usable landfill space. While some facilities have been closed because they failed to meet regulations, others are closing because they are full. In the U.S.,

DRAFT

Tipping Fees

Average

Data: Glenn, 1992

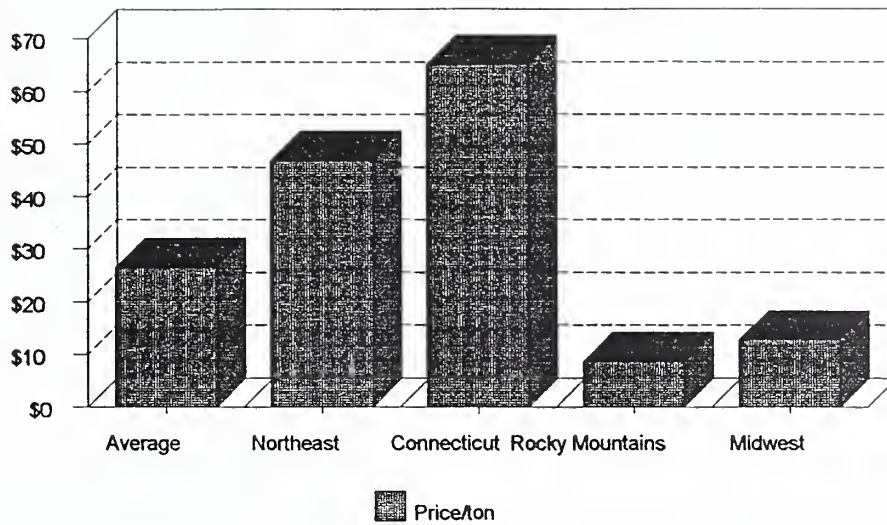


Figure 3: Tipping Fees

Landfills

In Operation

Data: Glenn, 1992

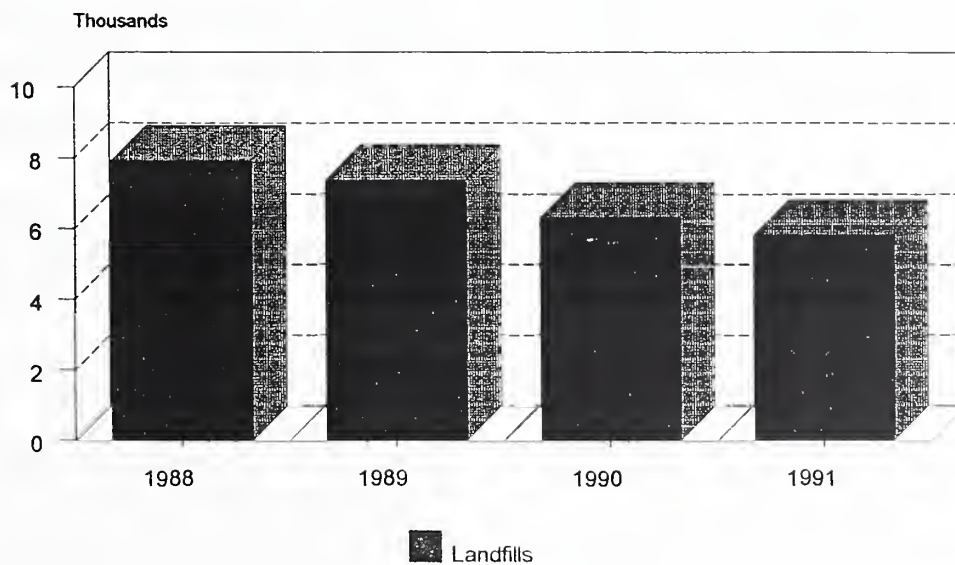


Figure 4: Landfills

there were 7,924 operating landfills in 1988, but only 5,812 by late 1991 (Fig. 4).

Costs for all types of processing systems are rising. In 1988, there were 115 U.S. composting facilities processing approximately 1,600 tons of dry sewage sludge daily. These facilities were constructed at a capital expenditure in excess of \$1 billion, and have operating costs estimated at \$100 million (Finstein, 1989).

A study of eight in-vessel composting systems revealed that each of the eight was using sawdust as an amendment, with a cost for the sawdust of \$3.92 to \$18.64 per cubic meter. Of these eight systems, the cost per dry ton of sludge processed ranges from \$100 to \$380 (Johnston et al., 1989).

Another analysis of 10 facilities, processing from five to 1,200 tons per day, shows capital costs ranging from \$250,000 to \$78 million, and operational costs from \$240,000 to \$30 million (Curtis et al., 1992).

The city of Scranton, PA built a sludge composting facility with a processing capacity of 25 dry tons of sludge (aerated static pile method). The cost of construction was \$3,338,000 and operational and maintenance costs were calculated at \$17.10 per wet ton of sludge processed (Elliott and Polidori, 1988).

F. Agronomic Uses of Untreated and Treated Wastes.

Nutrient Properties of Treated And Untreated Wastes

Municipal wastes have variable nutrient values (i.e., fertilizer value) depending on their source and treatment. Untreated wastes such as raw sewage sludge may be similar to animal manures with relatively high NAI and N and P contents. MSW are generally low in nutrients because they contain considerable paper and yard waste. Processes such as digestion or composting which result in the loss of

organic matter through decomposition will 1) increase concentrations of "conserved" (slightly soluble and non-volatile) nutrients such as P and trace metals; 2) decrease ammonia-N by volatilization; and 3) decrease potassium leaching.

The soils amended with sludge, the methods of sludge treatment, and the C:N ratio of the sewage sludge and the soil affect the mineralization of N (Barbarika et al., 1985; Douglas and Magdoff, 1991; Parker and Sommers, 1983), phosphorus (Soon and Bates, 1982; McCoy et al., 1986; McLaughlin, 1984) and sulfur (Taylor et al., 1978; Tabatabai and Chae, 1991). O'Keefe et al. (1986) and Douglas and Magdoff (1991) demonstrated that mineralization rates ranged from nearly zero to 60 percent of the organic N added; in general, the more extensive the biological treatment or degradation of the waste, the lower the N mineralization potential. Composting of sludges usually results in mineralization rates of about 10 percent or less (Douglas and Magdoff, 1991; Haan, 1981, Tester et al., 1977).

The benefits from composted products are determined by their maturity, mineralization in soil, and lack of plant toxicants. A biogenic waste compost can provide 60-90 kg available N ha⁻¹ at an application rate of 54.5 Mg ha⁻¹ (Vogtmann and Fricke, 1989), and an MSW compost can provide 90 kg N ha⁻¹ at a rate of 25.4 Mg ha⁻¹ (Mays et al., 1973). Evaluation of the fertilizer value of a compost includes the nutrient element and organic matter contents, mineralization rates, and C:N and C:P ratios.

Because of low levels of nutrients, composts are often considered more valuable as a source of organic matter; but when used in large quantities, composts are sources of slow-release nutrients. An application of 63.6 Mg ha⁻¹ MSW compost to phosphate-mining sand tailing's increased the soil content of extractable K, Ca and Mg (Hortenstine and Rothwell, 1972). Bengtson and Cornette (1973) found that an application of 40 Mg ha⁻¹ of MSW compost increased the concentration of exchangeable Ca in the soil after 28 months. Comparisons of MSW compost with mineral fertilizer showed that compost was unable to

maintain sufficient levels of available P (Cabrera et al., 1989), but compost additions did increase the potassium potential for the soil. Additions of a MSW compost on a sandy loam and a clay silt loam initially increased the percentage of organic carbon by 100 and 34 percent, respectively (Giusquiani et al., 1988).

Applications of 531 Mg ha^{-1} of a MSW/sewage sludge compost resulted in a 66 percent increase in the carbon content of the soil over 3 years (Zan et al., 1987b). Nitrogen increased from an average concentration of 0.12 to 0.15 percent, but the C:N ratio did not change. Phosphorus levels increased with the addition of compost. Applications of 9, 18, and 36 Mg ha^{-1} of MSW/sewage sludge compost over a 24 year period increased the total C and total N content and the N mineralization potential of the soil (Werner et al., 1988). The higher total N content was a result of higher hydrolyzable as well as non-hydrolyzable organic N compounds. The level of extractable P and S in a sewage-sludge compost amended soil is determined by the rate of P and S immobilization due to reactions with Fe and Al and the rate of P and S mineralization by the microbial population (Taylor et al., 1978). High P loading by septic tank effluent resulted in new P equilibrium values in soils (Sikora and Corey, 1976).

Ticknor and Hemphill (1990) found that a wide range of herbaceous and woody plants can be grown in undiluted yard waste compost (NPK content of 0-0.1-0.25). Supplemental fertilizer was necessary and additions of bark or pumice were beneficial for optimum plant growth. Vegetable market refuse composted with slaughterhouse waste increased yields of sunflower with increasing application rates (Marchesini et al., 1988); improvement occurred in several soil fertility factors.

Biogenic composts, made from separately collected food and yard wastes, have a relatively high fertilizer value (Vogtmann and Fricke, 1989); kohlrabi plants increased plant yield with biogenic compost and NPK-fertilizer.

MSW compost (pH8) with a relatively low C:N ratio of 17, and NPK value of 1.67-

0.55-0.40 produced a positive growth response in an acidic soil (Wong and Chu, 1985). Peach trees showed greater growth with MSW compost applications than with untreated controls, but had lower average fruit weights (Strabbioli and Angeloni, 1987). The average yield per tree was not significantly different, however. The NPK ratio for the compost was 1.4-0.15-0.2. Heavy applications of MSW compost ($102,204$, and 408 Mg ha^{-1}) caused poor growth initially, but had a significantly delayed fertilizing effect (Stone and Wiles, 1975). At 408 Mg ha^{-1} , normal growth was delayed by seven months. At the end of the experiment, these treatments had favorable yields when compared to treatments of 89.6 and $179.2 \text{ kg N ha}^{-1}$. An application of mature MSW compost at a much lower rate of 9 dry Mg ha^{-1} resulted in an increase in growth of *Brassica rapa* var. *pervidis* when compared with an equal application of nutrients in the form of mineral fertilizer (Chanyasak et al., 1983).

Compost applied in conjunction with mineral fertilizers increased yields compared to fertilizer or compost alone. Corn grain was increased from 3 Mg ha^{-1} to 4 Mg ha^{-1} for fertilizer alone to 10 Mg ha^{-1} for compost with fertilizer (Wang, 1977). Grass mixture yields increased from 14.0 g pot^{-1} with NPK fertilizer to 24.8 g pot^{-1} with a mixture of Dano compost and fertilizer (Kropisz and Kalinska, 1983). The dry weight of sorghum seed heads increased from 298 kg ha^{-1} with NPK applications and 206 kg ha^{-1} compost applications to 618 kg ha^{-1} with applications of both (Hortensine and Rothwell, 1972). Oat forage (dry weight) increased from 2144 kg ha^{-1} with NPK applications and 1405 kg ha^{-1} with compost to 3860 kg ha^{-1} with an application of a mixture. Physical changes in compost-amended soil, i.e., nutrient release, water, and improved soil aeration properties, allowed more efficient utilization of mineral fertilizer (Kropisz and Kalinska, 1983; Hortensine and Rothwell, 1972). For example, corn treated with 179.2 kg ha^{-1} of nitrogen plus 16 Mg ha^{-1} compost increased in productivity from 187.8 bushels ha^{-1} with either fertilizer or compost to 222.4 bushels ha^{-1} with both. The yield increase was thought to result from a synergistic effect of the compost and inorganic nitrogen since 16.3 Mg ha^{-1} of compost

Table 4. Examples of application of organic wastes to soils resulting in adequate plant growth.

Waste Type	Application Rate	Crop	Source
Sewage sludge compost	69-122 Mg ha ⁻¹	legumes, reed canary grass	Watkin and Winch, 1974
Sewage sludge compost	204 Mg ha ⁻¹	spruce and pine trees	Gouin, 1977
Sewage sludge compost	134 Mg ha ⁻¹	fescue	Tester, 1989
MSW compost	58 Mg ha ⁻¹	sorghum	Hortensine and Rothwell, 1973
MSW compost	45 Mg ha ⁻¹	carrot	Chu and Wong, 1987
MSW compost	64 Mg ha ⁻¹	bermuda grass	Wong and Chu, 1985
MSW/ sewage sludge compost	224 Mg ha ⁻¹	slash pine	Jokela et al., 1990
MSW compost	9 Mg ha ⁻¹	<i>B. rapa</i>	Chanyasak et al., 1983
MSW compost plus fertilizer	9 Mg ha ⁻¹	corn	Wang, 1977
Sewage sludge plus fertilizer	4.5 Mg ha ⁻¹	corn, winter wheat	White and Brown, 1981
Sewage sludge	134 Mg ha ⁻¹	corn	King and Dunlop, 1982
MSW compost	91 Mg ha ⁻¹	peas	Purves and Mackenzie, 1973

probably would not supply enough nitrogen or moisture for this magnitude of yield increase. Long term experiments (more than 100 years) have shown that recent crop yields benefited from the combined addition of organic matter and fertilizer (Johnston, 1987).

Fertilizer often generates better plant growth than compost alone because compost is often comparatively low in nutrients. For example, fertilizer increased dry weight by an amount from 190 to 1000 percent with *Brassica chinensis* and 18 to 190 percent with *Lycopersicon esculentum* when compared to varying compost rates (Chu and Wong, 1987). The *L. esculentum* fruit showed variable growth responses; some compost applications produced better yields than fertilizer. Carrots amended with 45.4 to 113.5 Mg ha⁻¹ compost yielded larger roots and foliage, and sorghum amended with 58.1 Mg ha⁻¹ attained greater height (Hortensine and Rothwell, 1973). Although nitrogen deficiencies were noted in

corn treated with unscreened MSW compost applied at rates of 8, 18, 102, 204 and 408 Mg ha⁻¹ without fertilizer, plots treated with 89.6 kg ha⁻¹ of nitrogen or 204 Mg ha⁻¹ of compost yielded 188 bushels ha⁻¹ as compared to 136 bushels ha⁻¹ without either amendment (Stone and Wiles, 1975). Dry sorghum forage yields increased from 10 Mg ha⁻¹ without compost or nitrogen to 15.4 Mg ha⁻¹ with 173 Mg ha⁻¹ compost and to 16.3 Mg ha⁻¹ with 179 kg ha⁻¹ N. A small application of MSW compost (12.7 Mg ha⁻¹) caused no noticeable growth difference between the compost treatment, a fertilizer treatment (500 kg ha⁻¹ of 15-15-15), and a mixture of the two (Cabrera et al., 1989). Highest yields of field and adzula bean were attained with compost-fertilizer combinations (Robinson, 1983). A mixture of compost and fertilizer has not resulted in a positive synergistic response in all cases.

Applications of co-composted MSW and sewage sludge (SS) have been at least as suc-

cessful as MSW applications alone. An MSW/SS compost applied to slash pine caused a 1.7 fold increase in the total stem biomass compared to control plots (Jokela et al., 1990), and a greater yield of maize compared to MSW compost alone (Zan et al., 1987a). Sorghum, common bermuda grass, and corn responded to annual applications of 130, 72.6 and 101.7 Mg ha⁻¹ MSW/SS (NPK of 1.3 - 0.30 - 0.91) compost, respectively (Mays et al., 1973). The yields were surpassed by applications of N at the rate of 180 kg ha⁻¹ together with adequate P and K. Applications of MSW/SS compost showed that forage yields of corn were higher than with the untreated control (Giordano et al., 1975). Bengtson and Cornette (1973) composted raw garbage which consisted mainly of paper; application of this compost (C:N 66.1) resulted in tree needles with a lower N content than the control and decreased soil acidity.

Songmuang et al., (1985) showed that long term applications of rice hull-manure compost eventually led to sufficient organic matter in the soil so that 12 Mg ha⁻¹ of compost could replace the fertilizer application. Similarly, Brinton (1985) hypothesized that long-term use of composted manure could eventually lead to a build-up of organic matter in the soil capable of supplying all the N needs of the plant. In the first year, the mineralization rate of composted manure was 9% of the total N added which equaled 20 percent of the NPK response of plants.

Application of MSW will result in accumulations of trace metals. Vineyards that had received several applications of municipal waste composts had 2-20 times the amount of metals in the soils (Furrer and Gupta, 1983). Jokela et al. (1990) studied a slash pine plantation which had been treated with 3 rates of garbage compost 16 years earlier; significant but modest treatments were associated with increases in concentrations of N, P, B, Fe, Al and Zn in pine tissues. Examples of the successful utilization of organic wastes in soils are summarized in Table 4.

Non-nutrient Properties of Treated And Untreated Wastes

Addition of sludge or compost to the soil almost always improves the physical properties. However, with certain types of composts, such as sewage sludge, it may take much more of the compost to affect physical properties of the soil than it does to provide the necessary nutrients for plants. Chang et al. (1983) reported that more than 72.6 Mg ha⁻¹ of sewage sludge compost was necessary to significantly affect the physical properties of the soil, i.e., aggregate stability, bulk density, porosity, organic matter content, and moisture holding capacity.

Soil aggregate size and stability are affected by the physical, chemical and biological activities existing in the soil, especially the microbial decomposition of organic matter. Aggregate stability refers to the ability of soil aggregates to withstand disruptive influences such as water and pressure. Organic matter in the soil provides a substrate for microbial growth; the microorganisms in turn produce substances such as polysaccharides which are necessary for aggregation.

Sewage sludges increase stable aggregates (Epstein, 1975) and water holding capacity (Khaleel et al., 1981), and decrease bulk density of soils (Khaleel et al., 1981). Although a wide range of application rates have been used in these studies, no minimum application rate has been recommended to achieve specific minimum physical changes.

Many reports indicate that compost increases the aggregate stability of soil. MSW compost applied at 9 Mg ha⁻¹ to a clay textured latosol increased aggregate stability from 56.78 to 59.10 (Wang, 1977). Applications of 27.2-54.4 Mg ha⁻¹ MSW compost to a Typic Haploxeralf increased aggregate stability, after 90 days, from 40.2 to 44.6 and 47.5, respectively (Hernando et al., 1989). Soil carbon content after 90 and 180 days was correlated to the aggregate stability. MSW compost at 36.3 Mg ha⁻¹ of organic matter was able to increase the water stability index in a Eutric Fluvisol after three years, but no re-

sponse was observed in a calcium-rich soil (Guidi and Poggio, 1987).

MSW compost applied at 9 Mg ha^{-1} to a clay textured latosol did not change the bulk density of the soil significantly (Wang, 1977). A MSW compost applied at several rates caused no change in the total porosity or pore size distribution in either a Calcic Cambisol or a Eutric Fluvisol after 3 years (Guidi and Poggio, 1987). After 5 years of sewage compost amendments, a loamy sand soil had reduced penetration resistance and bulk density, increased soil water content and specific surface area, and modified pH below the tillage depth (Tester, 1990).

Applications of MSW/SS compost at rates of 45.4 and 136.2 Mg ha^{-1} increased the porosity of a sandy loam soil (Guidi et al., 1981; Pagliai et al., 1981) and increased total porosity significantly and increased soil aggregate stability slightly (Pagliai et al., 1981).

An application of 63.6 Mg ha^{-1} of MSW compost on phosphate-mining sand tailings increased the organic matter content from 0.39 to 1.05 percent after one cycle of sorghum and oats (Hortensine and Rothwell, 1972). Applications of 27.2 Mg ha^{-1} of compost increased the organic matter from 1.6-2.1 to 3.3 percent (Gabriels, 1988). Duggan and Wiles (1976) showed similar results with compost additions up to 181.6 Mg ha^{-1} .

Elemental compositions, functional group contents, E4/E6 ratios and spectral characteristics were not useful for detecting differences in the structure of humic acids isolated from the soil before and after the addition of compost (Gonzalez-Vila and Martin, 1985).

The term "moisture holding capacity" indicates the amount of water a soil can hold while the term "moisture retention capacity" refers to the length of time a soil can retain water (Epstein et al., 1976). Both properties are greater in soils with large amounts of organic matter or clay particles (Einspahr and Fiscus, 1984). Although these two factors together indicate how much water is in the soil, they do not necessarily indicate the availability of that water for plant use (Chang et al., 1983). Heavy applications of MSW resulted

in decreased bulk density and compression strength, and increased soil moisture content and moisture holding capacity (Mays et al., 1973). Addition of non segregated solid waste increased aggregate stability, but the availability of moisture, as determined by relative soil moisture curves at 0.33 and 15 bar, was not increased (Webber, 1978). Composted and worm-worked sludges increased the available soil moisture of a sandy soil from 10.6 to 54.4 and 31.6 percent, respectively (Einspahr and Fiscus, 1984).

Applications of 9 Mg ha^{-1} of MSW compost increased the moisture holding capacity slightly at .33 bar (Wang, 1977); the moisture content during a dry period was higher in the soil amended with compost. Hortensine and Rothwell (1972) found that applications of 63.6 Mg ha^{-1} of MSW compost increased the moisture holding capacity after a one year rotation of sorghum and oats. Applications of 13.6, 27.2, and 54.4 Mg ha^{-1} of MSW compost increased the water holding capacity slightly throughout the 180 day monitoring process (Hernando et al., 1989) with the highest level of compost producing the largest increase. A MSW compost application of 40 Mg ha^{-1} in a young slash pine plantation increased the soil moisture retention ability, especially during the first months after the application (Bengtson and Cornette, 1973). Depending on the waste and the application rate, improvement in several soil properties were generally recorded.

Spreadability of Wastes

Waste products applied to soils are most beneficial if they are uniform in composition and texture. MSW usually is highly variable in organics, glass, plastic, and metals; increased uniformity results from segregation of the inert materials. Grinding or composting of the organic fraction will generally improve the uniformity and particle size distribution. Liquid or semisolid (<10 percent solids) wastes are more uniform and can be sprayed onto the surface or injected below the surface of the soil. In the latter case, the loss of nutrients by volatilization is greatly diminished.

Solid wastes can be 1) surface-applied with little or no tillage, 2) surface-applied and incorporated into the soil, 3) applied as a mulch, or 4) applied in a furrow or trough. The choice of application method depends on several factors including the size and uniformity of the waste, the nutrient content of the waste, the amount of waste available and the equipment available to apply the waste and to till the soil, and the crop. Large particle wastes with low nutrient content may be best applied as a mulch where revegetation is necessary or prevention of wind or water erosion is important. Small particle (<1 cm) wastes are easily and uniformly spread with commercial fertilizer and manure spreaders. Experience with manures and sludges indicates that non-uniform applications result in variable plant stands across the field.

Application of solid wastes in narrow trenches of less than 60 cm wide and 60 to 120 cm deep is generally considered a disposal operation because large amounts of material can be applied to small land areas. However, agronomic benefits can be obtained in areas where impervious boundaries exist in soil profiles. Deep trenches will penetrate the barriers and allow roots to penetrate into the lower soil layers. If the trenches are filled with organic material, significant nutrient benefits will be obtained by the roots.

Product Quality Standards

Product quality standards are related to proposed use of the solid waste (Table 5).

Table 5. Product quality standards for solid wastes.

Quality	Size Uniformity	Ingredient Analysis	Restricted Use Based on Toxicants	Restricted Use Based on Inerts	Probable Uses
Low	Uniformity and size analysis not necessary	Approximate analysis of nutrients	Nontoxic to hardy plants	2-5 % inert material	Revegetation of barren or disturbed land
Medium	Particle size within range for uniform application	Sufficient analysis to make applications to non-food chain crop	Nontoxic to moderately sensitive crops	Percentage below that considered injurious or unsightly	Agriculture, silviculture, turf amendments
High	Particle size within guaranteed range of sieve size	Guaranteed analysis	Nontoxic to sensitive plants	Percentage below that considered injurious or insightly	Potting mix, home gardens all food chain crops

Preservation of nutrients is best accomplished by mixing the wastes with the soil after application. Small particles are more easily mixed with soils especially in areas where minimal disturbance is desired. Furrow or slot application may be less uniform in particle size because this application method is a variation of a mulch application.

Techniques to Reduce Loss of Nutrients from Wastes.

Losses of nutrients from wastes by volatilization or leaching of soluble components can reduce their value for both agricultural and horticultural uses. Losses of key soluble components such as potassium and nitrate can occur by leaching. Volatilization of ammonia

from animal and sewage sludge wastes is a critical problem. Prevention of losses by leaching simply requires that liquids do not enter the waste and that excessive drainage from the waste does not occur. Proper storage of products is required in lieu of soil application.

Volatilization of ammonia occurs when 1) the pH of the medium is alkaline (8.0) or 2) when the solubility of ammonia in the solution is exceeded. Ammonia is a product of nitrogen mineralization in wastes and if either of the above conditions occurs, volatilization is probable. In order to prevent volatilization, the pH must be reduced to below 7.0 and/or the accumulation of ammonia reduced. Microorganisms use ammonia as a preferential N source and if activity is maintained at a relatively high level, ammonia will be transformed into organic N as microbial biomass. Sikora and Sowers (1985) found that ammonia volatilization occurred during the first 10 days in the composting of lime-stabilized sludge, but that only 10 percent of the total N was lost during this time. If microbial activity is inhibited, i.e., by high temperature, more N would be lost. Addition of P to wastes also reduces N loss possibly by stimulating decomposition of the wastes.

Research Needs:

Determination of the heterogeneity and range in chemical and physical characteristics of the components in municipal wastes is necessary so that maximal benefits can be achieved.

The application of wastes to soil as a complete fertilizer is not a viable option for utilization of sludges or composts. Many factors are involved in this conclusion, namely the amount of waste necessary versus the amount of waste available, the restrictions on adding excess nutrients other than the macro nutrients of N and P, the concern about accumulation of non-nutrient chemicals such as heavy metals in soils receiving wastes. Because of these restrictions, research on amendment combinations of wastes and mineral fertilizer is needed so that environmental, agronomic and economic factors are addressed in waste utilization.

The role of organic matter in the form of municipal or industrial wastes in maintaining or improving soil physical properties needs further clarification. Specifically, what amendment rates are needed to increase soil organic matter by 10 percent in 5 years? What amendment rate is needed to maintain present organic matter levels?

Agricultural and municipal waste streams can be mixed, but little data are available on the techniques, mixing ratios, benefits and potential uses of mixtures.

Blending of organics and industrial wastes needs to provide products that are tailored to specific applications. Bioavailability of metal and organic contaminants in some wastes needs to be reduced.

G. Horticultural Uses of Untreated and Treated Wastes

Products from the horticultural industry in the U.S. have an estimated value of approximately \$9 billion annually; this includes fruits, vegetables, flowers, ornamentals and landscaping. In 1991, containerized plant production accounted for a \$4.7 billion segment of the horticultural industry. Containerized growth media typically contain 60-70 percent organic substrata. The "Ball and Burlap" harvest of trees and shrubs from nurseries resulted in the removal of approximately 227 Mg of topsoil per year. Together the containerized and field sectors of the horticultural industry have a continuing need to replenish the organic matter lost through normal production and sales activities. Presently, the industry relies on imported Canadian peat, on domestic milled pine bark and shredded hardwood bark. Familiarity with the performance characteristics and nutrient composition of these growth media components encourages users to maintain the "status quo" unless it can be shown that new or alternative products have equivalent or superior properties to those currently in use. Waste reclamation managers need to recognize that, although recycled wastes represent a possible low cost substitute for peat and bark, the reclaimed organics need

to have a dependable standard of quality in terms of pH, soluble salts, particle size, macro- and micro-element content, moisture, and pathogens. There has been much interest in the U.S. and in Western Europe in the use of other organic materials, e.g., manure, MSW, sludge, and leaves, as substitutes for peat and bark.

Research has shown that untreated waste materials are often unsuitable for horticultural applications because of phytotoxicity, nitrogen immobilization, high salt content or structural incompatibility (Verdonck, 1988). The variety of compostable organic wastes from different industries that can be used in horticultural media are listed in Table 6. Composted waste often compares favorably with peat as a major component of horticultural potting media (Bugbee and Frink, 1989) because appropriate quality control of waste processing can be used to produce products that meet the required horticultural grade criteria (Table 7). Composting can stabilize wastes, reduce the water content for transport and storage, improve structural characteristics of the product

Table 6. Compostable Organic Wastes from Different Industries.

Industries	Materials
Agriculture	Cocofibres, cork, cotton seed hulls, poultry carcasses, rice husks, rice straw
Aquaculture	Shellfish waste
Food industry	Chaff, coffee and tea waste, food flavoring waste, fruit residues, hop waste
Paper industry	Bark, sludge
Pharmaceutical	Fermentation residues
Textile industry	Cotton wastes, flax residues, wool residues
Town wastes	Food store wastes, garbage, garden waste, grass clippings, leaves, night soil, restaurant waste, wood chips
Wood industry	Bark, sawdust

compared to the raw stocks, and eliminate certain phytotoxicity problems (Hornick et al., 1984).

Of the organic materials used in potting media, at least 40 percent could be supplied from sources other than peat or pine bark (Conover and Poole, 1983; Fitzpatrick and Carter, 1983; Marcotrigiano et al., 1985; Sanderson, 1980). Composted organic wastes, e.g., cranberry wastes, pharmaceutical wastes, food flavoring wastes, sawdust, and sewage sludge were all found to be acceptable in some form for incorporation into potting media for the culture of nursery and greenhouse plants (Bugbee and Frink, 1989). Properly managed composts, can reduce the need for fertilizer (Falahi-Ardakani et al., 1987). Containerized plants grow as well in mixes containing up to 50 percent MSW as in standard mixes.

Phytotoxicity and growth rate suppression, however, resulted if the MSW content was greater than 50 percent. The problems have been attributed to high content of soluble salts (Lumis and Johnson, 1982; Conover and Joiner, 1966; Sanderson, 1980), boron toxicity (Lumis and Johnson, 1982), poor aeration (Sanderson, 1980), and heavy metal toxicity (Chu and Wong, 1987). Phytotoxicity is associated with the presence of volatile fatty acids such as formate, and phenolic compounds, but is dependent on the species and age of plant. For example, early root growth may be inhibited in cress and tomato but not in ryegrass, pansies, salvia, or wallflowers (Keeling et al., 1991).

An active area of composting research has been the application of wood processing wastes to horticultural use. Bark, sawdust, and shavings of coniferous trees can be used for some purposes without composting to improve the physical qualities of horticultural mixtures. Up to 80 percent by volume of bark composts can be used in potting mixes or as substitutes for peat in growing many vegetable and ornamental plants (Pudelski, 1983, 1985). Short-term composting (e.g., 3 weeks to 3 months) with addition of nitrogenous materials (e.g., soy scrap sludge) 1) inactivates phytotoxic substances that may be present in the raw material, 2) corrects the C:N ratio and

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Table 7. Important horticultural properties of peat and composts made from separately collected organic wastes (wood, leaves, grass clippings) and desirable properties for horticultural growing media.

Quality criteria	Properties of		
	peat	compost	growing media
impurities (e.g. plastic, rubber, glass, stone, etc.)	none	low (very low if source separated and compost is screened)	no sharps or particle >2mm
growth inhibiting substances	none	none if composted properly	free from growth inhibiting substances
plant pathogens, viable seeds and plant parts	none	virtually none if composted properly	free from infectious pathogens, viable seeds and plant parts
heavy metals	none	organic household wastes low, in composted green wastes very low.	as a low as possible non-regulated non - food chain plants
volume weight (g L ⁻¹ dry matter)	40-80 (white peat) 120-250 (frz. black peat)	300 - 700 (1300)	200-400
porosity (% vol.)	very high 85-98	lower in all composts 50-80	as high as possible (75%)
water capacity(%vol.)	very high (40)-87	45-65	as high as possible (60%)
pH(CaCl ₂)	2.5-3.5	6.5-8.5	5.5-6.6
salinity	very low(<.5g KCl L ⁻¹)	average to high (max. 6.5 g L ⁻¹ in organic household waste composts; max 3.0 g L ⁻¹ in green waste compost.	as low as possible (max. 3.0 g L ⁻¹)
N (mg L ⁻¹) (plant available)	very low 0-80)	50-500	200 avg; 100-300
P ₂ O ₅ (mg L ⁻¹) plant available	none	high to very high	150 avg; 100-200
K ₂ O (mg L ⁻¹) plant available	very low (0-20)	extremely high (max 6000 mg L ⁻¹)	300 avg; 200-400
Mg (mg L ⁻¹) plant available	present (20-200)	high to very high	100 avg
trace elements	very low	no reliable resultsa	as recommended for plant type
organic matter(% vol.)	100%	99%	60-70%

thus counteracts sorption of mineral N, and 3) initiates humidification which aids in the water holding capacity of the mixture. Slow release fertilizers, e.g., Osmocote, Nutricote, and Plantacote containing necessary micro- and macro-elements are added.

Bark, sawdust, and wood shavings from hardwood species require longer composting times (e. g., 6 to 9 months) because of the greater amounts of phytotoxic substances requiring degradation. Beech bark compost is well recognized as a media component for growing vegetables in the field and in greenhouses (Baumann and Schmidt, 1981; Pudelski, 1980).

Sims and Pill (1987) found that tomato seedlings grow well in sphagnum peat amended with ≤ 30 percent (by volume) sewage sludge or poultry manure ($\leq 1 \text{ kgNm}^{-3}$). Incorporation of composted sewage sludge or poultry manure into growth media can eliminate the need for pre-plant fertilization. Gouin (1984) reported that a single N supplement of 600 mg L^{-1} , 2-3 weeks post-transplant was the only fertilization needed for bedding plants grown in potting media containing composted sewage sludge.

The capacity for organic materials in municipal wastes to absorb significant amounts of heavy metal cations, thereby reducing the availability and toxicity of the metals to plants, animals, and humans, suggests a potential for combining wastes to utilize this notable 'sink' feature (Jones et al., 1978). Addition of municipal leaf and street sand/sewage sludge compost to horticultural growing media did not increase the heavy metal content of container leachate (Bugbee et al., 1991).

Compost is being used successfully as a growing medium for sod production. As much as 189 m^3 of sewage sludge compost, leaves or other yard waste are used per hectare to grow sod on a plastic liner; less water is needed than in typical production practices and is combined with natural weed reduction (Anonymous, 1991b).

Plant Disease Suppression

Organic matter, e.g., green and animal manures and composts, are well known to affect crop production in agricultural soil. Among the many benefits described (USDA, 1978), the effects on plant disease stimulation and suppression are the least thoroughly understood. Soilborne diseases result in losses of more than \$4 billion annually to U.S. agriculture (James, 1981). Compost made from a variety of organic materials can control plant diseases caused by such soilborne pathogens as *Phytophthora*, *Pythium*, *Rhizoctonia* and *Sclerotinia*. Currently, inconsistency in maturity, and horticultural and microbial quality of composts makes it difficult for the nursery industry to rely on them categorically as major components for container media. New methods for predicting compost maturity are available and they can be used to enhance the quality and disease suppressiveness of composts (Inbar, Chen, and Hadar, 1989).

Following a 4 month curing period, the compost should be mixed with other container media components and allowed to stand for 3-4 weeks prior to use (Kuter et al., 1988). This is sufficient time for saprophytic microflora responsible for biocontrol of specific plant pathogens such as *Pythium* and *Rhizoctonia* to become established (Kwok et al., 1987). Because of differences in the amounts of microbial biomass present in composts as well as differences in bulk density, up to 55 percent (v/v) composted pine bark can be used in potting mixes, but only about 15 percent (v/v) composted SS can be used (Hoitink et al., 1991). Similar information about MSW compost needs to be obtained.

Research Needs

Quality and maturity criteria for composts produced from various sources relevant to horticultural uses need to be developed. This is a critical component for market development.

Research is needed to develop process technology for co-composting sewage sludges and the biodegradable fractions of MSW to enhance product quality and acceptability for agricultural and horticultural use. The feasibility and practicality of improving the agro-

conomic value of MSW as biofertilizers, possibly through such means as "spiking" or enriching them with chemical fertilizers need to be determined. In view of the increasing closure rate and costs of landfilling, enhancing the safe and beneficial use of MSW/SS in the vast horticulture industry in the U.S. may provide the lowest cost recycling/disposal option.

Methods need to be developed to dependably enhance the microbially-mediated plant disease suppression characteristics of compost. This would significantly lessen the need for biocides in the horticultural industry and would reduce multipoint sources of pollutants in run-off water.

Methods need to be developed to reliably inoculate horticultural grade composts with beneficial rhizosphere microbes that can biologically mediate nutrient uptake by the plant thereby reducing the dependence on synthetic fertilizers and the resultant nutrient leachate

H. Competitive Uses.

Incineration, composting and recycling are increasingly significant alternatives to landfilling; incineration has increased by 50 percent (Clarke, 1992). Ideally, waste processing begins with source reduction, followed by recycling, then composting, with the remainder incinerated or landfilled (Fig. 5).

Yard waste composting facilities have more than tripled between 1988 and late 1991 (Fig. 6), and curbside recycling programs have nearly quadrupled (Fig. 7). Material recovery facilities (MRF) have increased from 16 to 191 since 1988 (Fig 8).

Paper is one of the more routinely recycled products. By late 1990, it sold for between \$27.50-\$30.29 per Mg for corrugated and \$154-\$198 per Mg for computer paper. Newsprint has experienced a negative market because of the insufficient number of processing facilities available (Anonymous, 1991a). However, by 1990, there were 25 newsprint mills in the U.S., of which nine used secondary fiber to recycle newsprint. Of the 5.0 million Mg of newsprint produced yearly, 1.2 million Mg (Fig. 9) are recycled into news-

Waste Disposal

Data: Glen 1989-1992

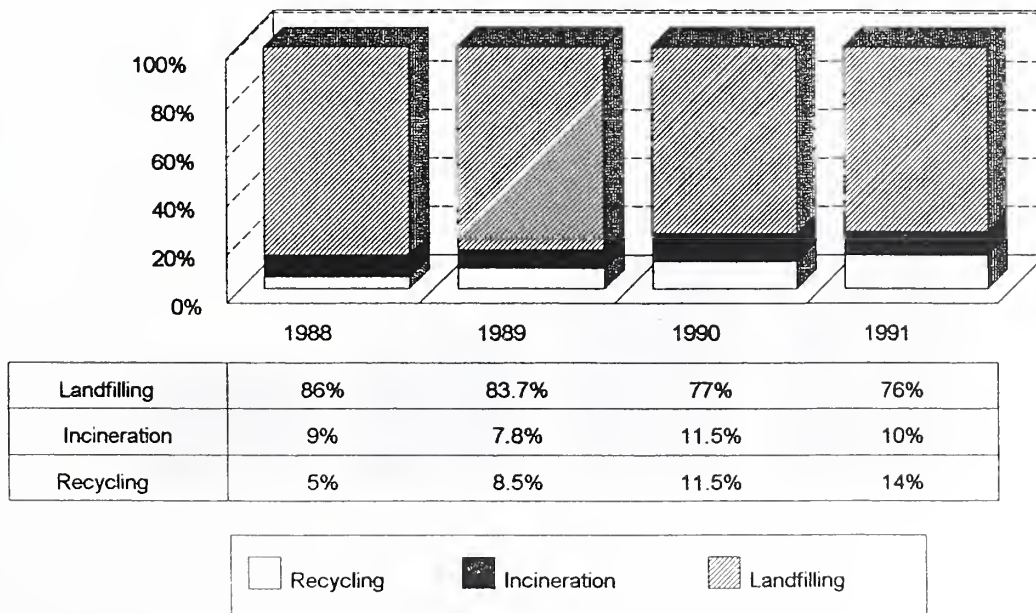


Figure 5: Waste Disposal

Yard Waste Programs

In Operation

Data: Glenn, 1992

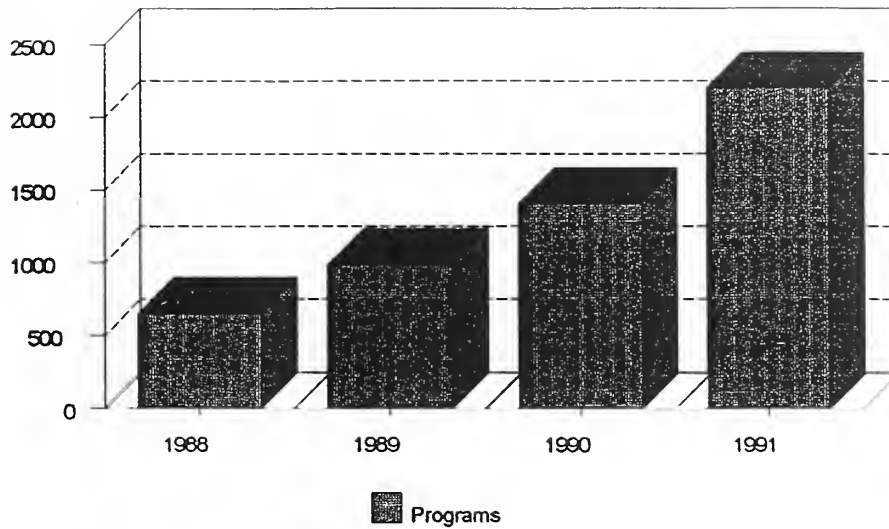


Figure 6: Yard Waste Programs

Curbside Recycling

Programs in Operation

Data: Glenn, 1992

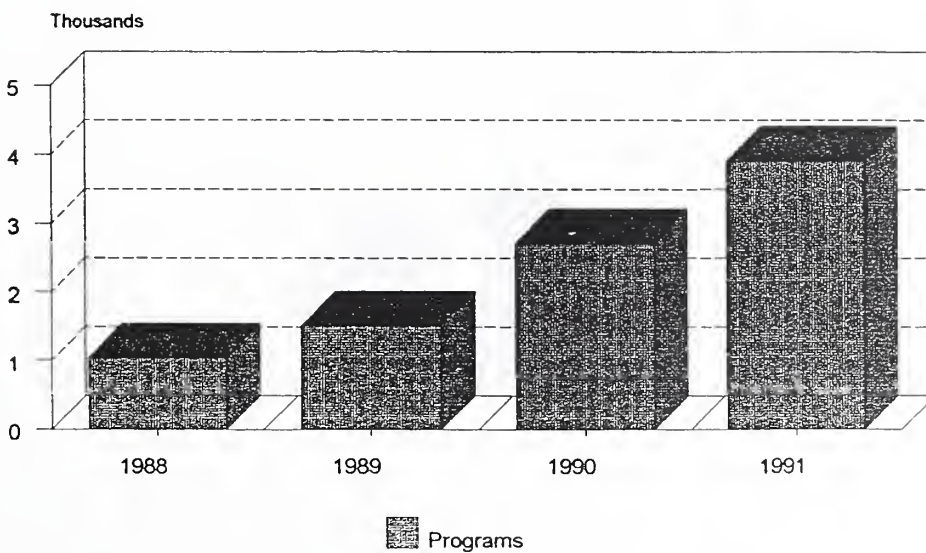


Figure 7: Curbside Programs

MRF Programs

In Operation

Data: Glenn, 1992

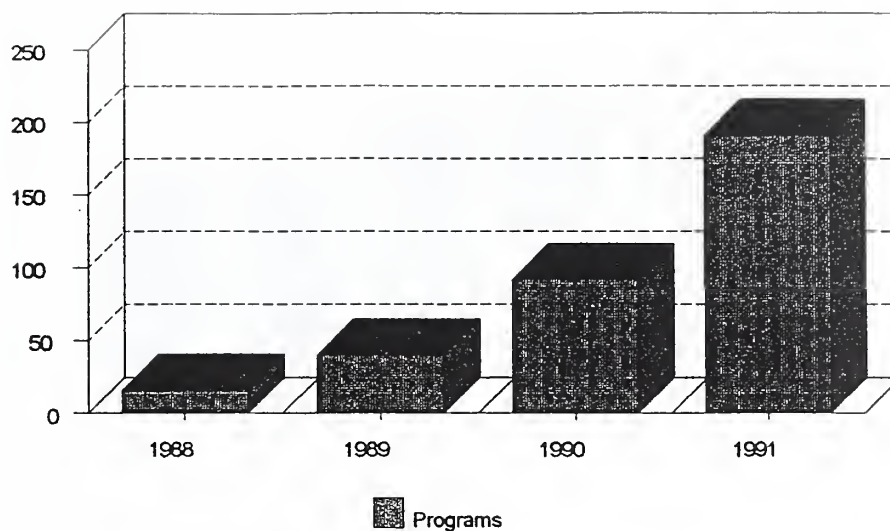


Figure 8: MRF Programs

Newsprint

Million Tons Per Year

Data: Sparks, 1990

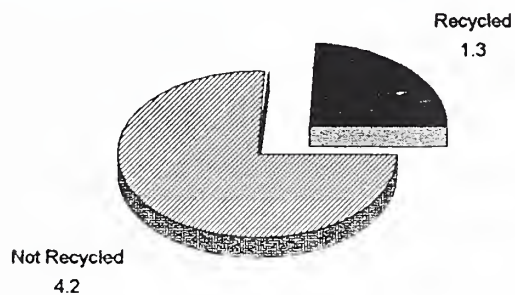


Figure 9: Newsprint Processing

Sludge Composting

Projects in Operation

Data: Goldstein and Riggie, 1990

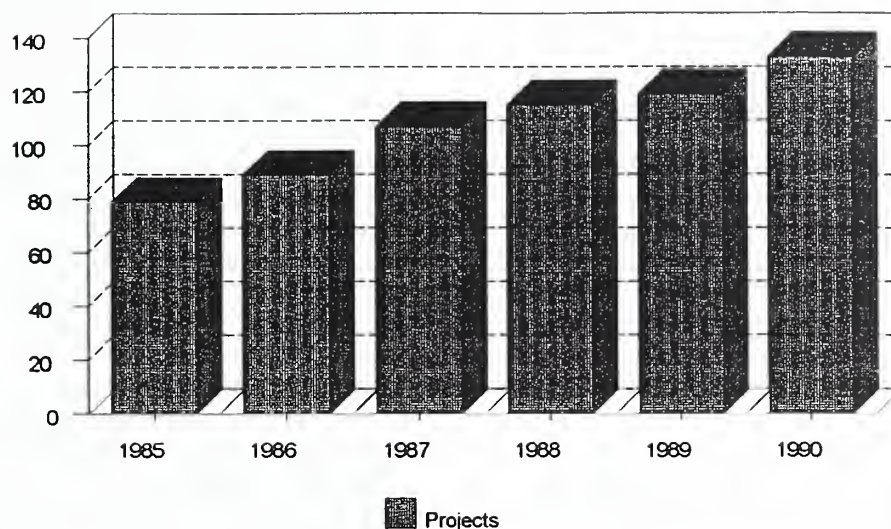


Figure 10: Sludge Composting Projects

print (Sparks, 1990). Some of the remaining newsprint is used as animal bedding or as bulking agents for composting, much of the remainder is either incinerated or landfilled. Five towns in Eastern Long Island have formed an alliance under a New York Department of Environmental Conservation grant and have doubled recycling rates from four to 10 percent; the newsprint is recycled into insulation, animal bedding and soil additives (Arner, 1991).

Annually, about 544,800 dry Mg of sewage sludge are generated by approximately 11,500 publicly-owned waste water treatment facilities (Finstein, 1989). The number of sludge composting facilities (Fig. 10) increased from 61 to 133 operating plants from 1983 to 1990 (Goldstein, 1988; Goldstein and Riggie, 1990). Mixed waste composting is increasing, with 18 projects in operation and at least seven under construction.

MSW composting is not a simple solution to landfill reduction. Between 10 and 20 percent of the solid waste stream is diverted through materials recovered. After compost-

ing, screening removes reject materials ranging from 10 to 30 percent by volume of the mixture. The reject material is landfilled with normal tipping fees assessed by weight (Goldstein and Spencer, 1990). By mid-1991, the vast majority of MSW compost ended up in landfills as either cover or fill. This resulted from the fact that many compost production facilities regarded composting as a means of volume and weight reduction, rather than as a means to produce a highly desirable horticultural matrix or landscaping material. Quality production requires that MSW composting facilities view their processes as manufacturing operations with an end product to vend rather than to dump (Richard, 1992).

Substantive efforts in market development for compost will be required. In a November 1990 survey of four MSW composting facilities that were marketing compost in Minnesota, Delaware and Florida, only the Delaware facility reported income from marketing the composting product (Spencer and Goldstein, 1990). Memphis, Tennessee, operates a large facility known as The Earth Complex which combines sludge and

yard waste composting with landfilling and a proposed methane recovery system (Riggle, 1991). In Austin, Texas, the Hornsby Bend Waste Water Treatment Facility processes about 227 million liters of waste water daily from which it extracts 40.9 to 45.4 dry Mg of sludge. The majority of the sludge is windrow composted followed by distribution and marketing under the name Dillo Dirt; Dillo Dirt is a registered trademark of the State of Texas. Dillo Dirt is available to all city departments without cost and to registered vendors at \$6.50 per cubic meter. During most of the year, demand far exceeds supply. Texas and the U.S. EPA released Dillo Dirt for general use, but recommended that it not be used for growing crops for human consumption (Doersam and Armstrong, 1992).

Applications for composted solid waste are currently being developed. Studies show potential uses outweighing current production by a margin of 47 to 1. The largest potential use is in agriculture (Slivka et al., 1991). Research projects are underway at the University of Maryland with the Solid Waste Composting Council, and in New Jersey with private companies, Rutgers University and the New Jersey departments of Environmental Protection and Energy, Commerce, and Agriculture in a Compost Utilization Program. These programs are designed to study the potential agricultural uses for composted solid waste (Anonymous, 1992).

Constructed wetlands are being designed and implemented to treat waste water. By late 1990, there were 154 systems in operation or in design and/or construction, including systems that can treat as much as 454 million liters per day (Reed, 1991).

Some progress is also being made to reduce the production of toxic and/or non-compostable materials. Many printers are testing and using soy-based inks. Packers are using biodegradable materials with less bulk and toxins.

The list of uses for recycled or composted materials expands daily. Processed garbage has been tested as a filler in concrete with good results in non load-bearing situations. The processed garbage in the mix re-

sults in lower thermal conductivity, lower capillary suction and lighter weight (Zhang and Whittmann, 1991). Coal fly ash, the residue of coal-fired electrical generators has been added to cement, sand and water to produce Lytag-concrete, also known as power concrete. This mixture is almost as strong as and can be used as a general substitute for gravel concrete. Lytag concrete weighs 20 percent less than gravel concrete and has less potential for cracking during hardening (Faase et al., 1991).

Coal-fly-ash amended composts resulted in increased availability of nutrients over compost or fly ash alone indicating a chemical reaction and mineralization of N during the composting process. This resulted in a more efficient plant utilization of nutrients when 20-40% of fly ash amended compost was applied to the soil (Menon et al., 1992).

More than 200 million tires are disposed of annually. Some are reused after retreading or recapping, others find new life in the creation of playgrounds or reefs (Sienkiewicz, 1990). Tires can be ground and mixed with asphalt, to make an asphalt rubber, or can be used as a rubber-modified asphalt concrete (RUMAC) for road paving (Anonymous, 1991a). Also, tires can be processed into chips that can be burned as a substitute for high-grade bituminous coal (Sienkiewicz, 1990) or used as a bulking agent during composting.

Most of these resources used as substitutes for new materials are currently more expensive than the traditional ones. However, when the waste reduction is taken into account, the cost of recycled materials is closer to the price of new materials. Lack of regulations, and time and funding for testing and classification of various composts have caused delays in the development of marketing programs for solid waste compost products.

Research Needs

Develop methods for classifying and grading compost and wastes for specific uses. This will support development of marketing programs for MSW/SS compost and wastes.

I. Potential Barriers and Constraints

Public Perceptions and Socio-Political Issues

Waste composting has a consistent appeal to the public because it is viewed as an environmentally beneficial and economical way to return nutrients to soils and to transform unusable material into a valuable commodity. Several states presently permit MSW composting and co-composting as part of local solid waste plans. In most areas, land application of municipal wastes is regulated by federal, state, and county agencies. For local areas, composting MSW is viewed as a way to avoid the burden of providing disposal for other localities. Large centralized municipal waste facilities can be supplanted by smaller and simpler community-based composting facilities. However, odor management remains a concern for citizens adjacent to even smaller facilities. "Word-of-mouth" carries a sizable market impact, and poor public opinion can jeopardize the future of compost facilities siting and operating decisions. Public opinion is not necessarily the major factor presently influencing the growth of MSW composting and facility siting, but is likely to carry more weight than in the recent past if these facilities come to be regarded as little more than disposal capacity savings efforts" (Miller and Golden, 1992). Many source separation projects currently in place would require expansion to provide the quality MSW needed to produce marketable compost. This will require a coordinated effort at the local level and involve a public education and information component.

Odor

Odor management is a necessity for successful composting of sewage sludges, yard wastes, manures, food wastes, municipal solid wastes, and other organic substances (Walker, 1993; Miller, 1993; Williams and Miller, 1993; and Dunson, 1993). Although com-

posting can transform very odorous wastes into useful soil conditioning and low analysis fertilizer products, it also can generate odors if the process is improperly managed. Considerable information is available characterizing odors from composting materials; new methods are being developed to abate and control their production and dissemination.

Odors may be controlled by optimizing the composting process to minimize anaerobiosis, maximize microbial metabolism of odorous substrates, and by collecting, treating and dispersing those odors that are formed. A crucial part of planning for treatment is identifying and characterizing odors and predicting their transport by use of appropriate models. Ideally, these planning and modeling activities will have preceded the design and operation of the composting facility. More often than not, however, control efforts have been initiated only after community opposition has threatened to shut down the facility. A more proactive approach is needed in the future.

Control of odors can focus not only on treatment of odors, but on their prevention based on a fundamental understanding of the ecological conditions favoring their production. Many of the control strategies which reduce odors during processing can reduce a broad spectrum of odorous compounds, as the conditions for their generation are similar. This is an advantage over chemical treatments which might require a number of unit processes needed to address different chemical classes.

With the increasing availability and economy of gas analysis by gas chromatography coupled with mass spectrometry (GC/MS), it is becoming apparent that hundreds of odorous materials can be found in almost any suspect sample, and that some of those will be present at concentrations above their usual odor threshold. Card (1989), Hentz et al. (1992) Patterson et al. (1984) and Van Durme et al. (1992) have all published GC/MS analyses of odorous air from various sources around wastewater and sludge processing facilities, including composting plants. Hydrogen sulfide seems to cause odor problems in mainly acidic oxygen-starved points in wastewater treatment or anaerobic windrows.

Odorants from properly operated sludge composting plants typically arise from more alkaline and oxidizing environments, which are chemically more similar to rendering than to wastewater treatment plant emissions. Ammonia, dimethyl disulfide, and terpenes such as limonene, are generally present at concentrations above their odor thresholds, along with relatively less odorous compounds such as methyl-ethyl-ketone, terpene alcohols and alkylbenzenes.

Odorous compounds can be grouped into families having similar behavior with regard to potentially useful abatement processes.

The major families (examples) of odorants are:

semi-volatile compounds (isoborneol) removable by condensation;

volatile compounds (limonene) removable by sorption;

alkaline compounds (ammonia) removable by acidification;

acidic compounds (butyric acid) removable by alkalization;

reducing compounds (dimethyl sulfide) removable by oxidation;

oxidizing compounds (dichloramine) removable by reduction.

The major families of treatment processes are:

condensation - thermal or steam swept, or activated sorption;

Neutralization - with organic or inorganic acids or bases;

oxidation/reduction - with air, organic or inorganic reagents.

Odorant families likely to be emitted can be predicted based on a "phase diagram" using sulphur/carbon ratio; nitrogen/carbon ratio; and (available oxygen)/(oxygen demand) ratios. Given the likely odorant families, ra-

tional pretreatment strategies and odorant treatment processes can be compared in terms of needs for resources such as capital, operating costs, manual labor, operator training, and maintenance training. It is usually found that process options, which decrease the air volume that needs to be treated, generate large savings, and that properly applied chemical pretreatment, compost operations, gas cooling, and air auto-oxidation reactions, are cheaper than in-stack abatement reactions with chemicals.

Biofilters have been used as a means to treat odorous compounds and potential air pollutants in gas streams from waste water facilities, solid waste processing facilities, rendering plants, chemical manufacturing facilities and composting facilities for several decades. In recent years the interest and use of biofilters for odor control in composting facilities has increased dramatically. Organic and inorganic compounds in the gas phase which are biodegradable can be treated to a high degree of efficiency (ie., greater than 95% removal). A number of pilot and full scale studies have shown that a high degree of odor removal can be achieved by biofilters. Further development of engineering information is needed as related to media selection which provides optimal absorption capacity, while minimizing system head loss and providing an environment suitable for the proliferation of microorganisms which oxidize odorous compounds.

Pathogen and Parasite Destruction

Extensive research on destruction of human pathogens in sludge compost has yielded reliable time-temperature indices for inactivation of viruses, enteric bacteria, fungi, protozoa, and parasites (Burge et al., 1978; Burge et al., 1981). A review (Burge and Enkiri, 1978) of the somewhat limited research done on the infectious disease hazard of land spreading of sewage waste revealed that "most sewage-related disease outbreaks have been attributed to the use of raw sewage waste water, raw sludges, or night soils on food crops consumed raw, to contamination of drinking water from septic tanks, or to con-

sumption of raw shellfish from sewage-polluted waters." Surface movement of water could increase the hazard for pathogen distribution, but lime stabilization of raw sludge could reduce the hazard significantly by inactivating pathogens. In contrast to composting, other methods of pathogen destruction did not leave the sludge stabilized and non-putrefactive. Regrowth of human pathogens and their indicators is negligible or non-existent in sewage sludge compost (Burge et al., 1987; Husong et al., 1985; Millner et al., 1987), whereas certain plant pathogens can colonize compost, if the indigenous microflora is insufficiently suppressive (Hoitink and Poole, 1980; Hoitink et al., 1991). Plant pathogens (viruses, bacteria, fungi and nematodes) are also destroyed by self heating of the organic mass when sufficiently high temperatures are achieved for appropriate time periods (Hoitink and Fahy, 1986).

Time-temperature criteria for destruction of human and/or plant pathogens in MSW, farmyard, leaf or yard, and food processing waste composts or any of these materials co-

composted with sewage sludge can be expected to be very similar to those applicable to sewage sludge (Fig. 11). However, there are no specific data on these alternative combinations of feed stocks and some demonstration research needs to be done to substantiate this extrapolation.

Water Quality Factors in Relation to Waste Disposal on Land

Reducing the impact of agricultural practices on ground and surface waters has been a goal of farmers and government officials for decades. A number of key factors have evolved from research efforts in this area. They include adding wastes to soils only in amounts which equal the nutrient requirement of the crop for that season. Because nitrogen in its soluble form does not bind appreciably to soil particles, application rates are generally adjusted to the "potentially" mineralizable N content of the entities or to reduction of N in leachate even though the possibility

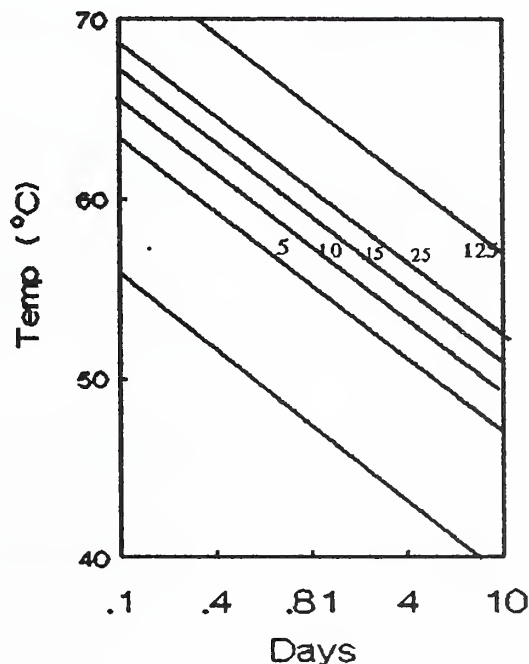


Figure 11. Curves Showing the Time by Temperature Regimes Necessary for the Inactivation of a Desired Number of Logs of f2 Bacteriophage.

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Motor Oil

Million Liters Per Year

Data: Sienkiewicz, 1989

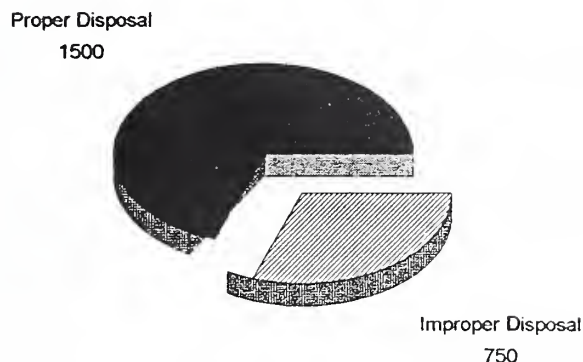


Figure 12: Motor Oil

definitely exists (Sowden and Hore, 1975; Sikora et al., 1979).

Phosphorus in waste is sometimes added in excess of the plant needs, but the form of P in wastes and the soil type greatly affect the movement of P through the soil profile (Sikora and Corey, 1976); this often results in more P being absorbed than predicted. Because of the soil's ability to remove P from percolating leachate, the occurrence of P pollution in ground water is rare.

The enrichment of surface water by run-off from land amended with organic wastes or fertilizers is of genuine concern. Soil conservation practices such as contour tillage, use of buffer strips, and residue management control losses from fields. Information on the effectiveness of these practices was gained from "Overland Flow" treatment of wastes (Tedaldi and Loehr, 1990). In general, the slope of the land, the infiltration capacity of the soil, the vegetation present, and the volume of rainfall in any one event will deter-

mine the probability of nutrient run-off and surface water pollution (Wendt and Corey, 1980; Sharpley et al., 1981; Ahuja et al. 1982).

Because these practices are recommended and/or enforced in highly erodible soils, research in this area is not of high priority. Compliance with suggested farming practices will reduce the enrichment of ground water or surface water by nutrients or chemicals from all amendments.

Metals and Organics.

In their effort to reduce the volume of materials being sent to landfills federal, and state agencies have promoted the composting of leaves and yard waste. However, the environmental impacts of such operations have not been sufficiently researched or evaluated specifically with regard to the environmental fate of nutrients, metals, and pesticide residues. Previously most research focused on the mechanics of composting. Information still is

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Table 8. Limitations to Working with Farmers to Manage Municipal Yard Wastes^a

Limitation ^b	Factors	Strategies
Transporting materials to the farm	Coordination of collectors/haulers and farmers Distance to sites differences among materials	Have a broker (public or private) serve several municipalities
Reliability	Availability of fields - during inclement weather -during growing season Security arrangements	Ill.-weather drop-off/storage site, Multiple sites Provide compensation, Negotiate a contract
PA-DER regulations	Hard to understand Ambiguous and inconsistent Anti-regulation attitude Future change could create a liability	Coordinate with manure management guideline. Rewrite in "farmer friendly" format Err to caution Work with PA-DER and local agencies
Contamination	Trash Pesticides	Design collection system to minimize trash Educate residents on where materials are going Provide compensation Provide for disposal of trash in yard waste at no cost to farmer Preliminary data shows these are not a a problem. More research needed to allay fears Reduce potential through a residential program that promotes minimizing pesticide use, grass recycling, and not cutting sprayed lawns for several days
Costs (other than for collection and transportation)	On-Farm: equipment, operations, site improvements, guideline compliance Municipal: administration, personnel	Direct compensation: Tipping fees (per ton or cubic yard), Flat fee for season, Hourly wage, Cost-share: PA-DER recycling grants, USDA's ASCS, Other, e.g., EPA's Chesapeake Bay Program Compare to avoid costs
Education	Awareness Participation	Include in DER yard waste manual Increase visibility of programs Host or attend field days, workshops

^a From Oshins, C., and K. Kelvin. 1992. On farm composting of municipal organics. *Biocycle*, 33(7):50-51.

^b Listed in order of most frequently cited.

needed on (1) the range and quantities of toxic residues in yard waste; (2) degradation of residues during composting; (3) leaching of residues into soils and water during and after composting; and (4) concentrations of toxic constituents in finished (marketable) products.

A reported survey of 9 composting facilities in the U.S. showed that the mean levels of potentially toxic metals in MSW compost were about half the mean levels in sludge compost (Walker and O'Donnell, 1991). However, there still is a need to determine (1) whether MSW composts are similar to composted SS in terms of the capacity to limit bioavailability of metals; (2) the extent of microbially-mediated degradation and/or immobilization of potentially toxic metals and synthetic organics; (3) safe and beneficial methods for decreasing the bioavailability of toxic metals and synthetic organic contaminants in MSW compost; (4) reliable methods for achieving rapid stabilization of composts; and (5) new methods for compost stability.

Very limited data are available on the occurrence and fate of organic toxicants in yard wastes. High temperature destruction of toxic compounds, e.g., dicamba and trifluralin, requires 427 degrees C (800 degrees F) (Kennedy and Stajanovic, 1969), an unachievable, undesirable temperature for composting. At 65 degrees C. (149 degrees F), 28 percent of 2,4-D in MSW compost was degraded (Snell, 1982).

Much of the risk of contaminants in MSW are eliminated by upfront processing of the input waste stream. In addition to improving the compost quality, separation of materials leads to much increased materials recovery (Glenn, 1991), and avoidance of especially hazardous materials such as polychlorinated biphenyls (PCBs) and cadmium. The disposal of motor oil in MSW is still a problem. Of more than 2250 million liters of motor oil waste generated annually, 1/3 of the used oil, or 750 million liters, is poured on the ground, into storm drains or put into the trash (Fig. 12). The used oil contains carcinogenic and other toxic substances, including large amounts of lead. Spread on land, motor oil will reduce soil productivity and contaminate ground water. Not only is there a risk of direct

consumption in contaminated water, but plants accumulate the toxic substances and become hazardous for humans and animals. An EPA report shows that one liter of oil will foul the taste of 1,000,000 liters of water. Used motor oil does not need to enter the waste stream, but can be recycled as a valuable resource. It can be re-refined and re-used as motor oil or as heating fuel (Sienkiewicz, 1989).

Mixing of Wastes for Composting—A Critical Step

Composting is a self-heating biological process which begins with the decomposition of organic material and ends when energy, moisture or oxygen is limiting. To achieve maximum degradation, it is critical that these limits not be imposed prematurely by improper combinations or mixing of ingredients, such as with material that is too wet (reduces oxygen exchange), too dry (reduces biological activity), or incompletely mixed ("pockets" of composted material as opposed to composting of the entire mass. For successful composting, mixing of the wastes is, therefore, the most critical step after ingredient quality.

Several types of mixers are appropriate for compost production. Batch mixers such as those used to mix livestock feed are successful for several ingredients (Rynk et al., 1992). Others include rotary drum mixers, pug mill mixers, and windrow machines (Willson et al., 1980). When wastes are an assortment of odd sizes such as grass clippings and tree limbs, shredders, grinders or hammer mills can be used to prepare uniform sized particles. For farm use, front end loaders or manure spreaders have also been successful as mixers (Rynk et al., 1992).

When waste mixtures are too wet, additional dry ingredients can be added. When wastes are too dry, additional water can be sprayed over the contents during the mixing process.

Various manipulations increase time and labor costs that must be considered in the final use of the compost. The more uniform and stable the compost, the higher its value. Mix-

ing is critical to achieve both uniformity and stability in the final product.

Limitations to On-farm Composting of Municipal Organics

Interest in on-farm composting of municipal leaves, food and other organic materials has been increasing as the potential for reduced disposal costs to municipalities, extra income to farmers and soil humus are recognized. With such advantages the question arises: "What are the limitations to on-farm composting and how can they be overcome?" In 1991-92, the Rodale Institutes' Rural/Urban Resource Center (Kutztown, PA) studied opportunities for municipalities and farms to work together to manage rural and urban wastes. The goals were to identify the limitations and develop strategies for overcoming them, and to identify information needs.

Collectively, six general limitations were identified (Table 8). These limitations include: (1) transporting the material to the farm; (2) farmer reliability; (3) Pennsylvania's Department of Environmental Resources (PA-DER) regulations; (4) contamination; (5) costs; and (6) education. Key strategies to overcome these limitations include farmer compensation, resource coordination, and streamlining of regulations.

The study was conducted in two phases. The first phase involved: (1) surveys of 60 selected municipalities which provided a cross section of demographic areas, from rich agricultural lands to rapidly urbanizing areas; and (2) interviews of 71 municipal officials (elected officials, recycling coordinators and public works directors). The second phase involved a series of "focus groups", each comprised of mixed personnel (farmers, municipal officials, county personnel and private interest groups) to rank the limitations in order of importance and to brainstorm on solutions. The identified limitations and solutions are shown in Table 8.

A primary conclusion from the Rodale study (Oshins and Kelvin, 1992) was the need to develop methods for compensating farm-

ers. The value of the service that the farmer is providing to the municipality must be recognized and adequately paid for. Although some municipal wastes do have a value to the farmer, research has shown that the costs of processing the material exceed the value. Tipping fees or contracts could compensate the farmer for direct costs of utilizing the materials; it also addresses the reliability issue. Compensation would give the farmer an incentive to stay with the program and would provide a sense of responsibility, obligation and value.

A second conclusion (Oshins and Kelvin, 1992) recognized the importance of an intermediary in coordinating the municipal-farm connection. A broker can coordinate the delivery of materials from several municipalities to several farms more easily than individual farmers or municipalities. The highest rate of diversion of materials to farms occurs where brokering systems exist (Anonymous, 1991c).

A third conclusion (Oshins and Kelvin, 1992) identified the problem of government regulations. Existing guidelines were initially written for municipal audiences, and were difficult for farmers to decipher. Co-composting municipal waste with farm manures has frequently not been addressed in either municipal waste guidelines or manure management guidelines. The need to develop "farmer friendly" guidelines for agricultural utilization of municipal wastes must be addressed.

When developing waste reduction/recycling strategies, municipalities should consider involving local farmers, and comparing farm use to other available options. Farmers often have the land, equipment and knowledge to compost more cheaply than a municipality. The farmer can also be the end user of the compost to increase the soil's productivity, tilth and overall health, while simultaneously reducing the output transportation costs to the producer.

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Foreword

Agricultural Utilization Of Animal Wastes

Agriculture both produces and utilizes wastes. Because of the potential for environmental degradation, there is major concern for those wastes associated with confined animal production enterprises. Although crop residues are another major by-product of agriculture, almost all crop residues are left in the field for soil and water conservation and nutrient recycling, and generally do not constitute a problem. On the other hand, by-products from the animal production enterprises, especially manures and dead animals, do result in a major utilization problem that can cause serious environmental pollution if not properly managed.

Inappropriate handling of animal wastes can result in degraded soil, water, and air quality. Such actions can also create social problems and generally reduce quality of life. However, these by-products of animal agriculture can also provide a number of beneficial effects, especially when wisely recycled as a source of nutrients for crop production. In addition, incorporating these materials into agricultural soils can improve soil physical conditions, water relations, and biological activity. A small percentage may also be used for other purposes - methane generation, refeeding, composting, and related uses.

Collectively, the livestock produced in the United States generate about 170 million Mg (187 million Mg ton) of manure (dry weight) annually. This manure, including urine, contains about 7.5 million Mg (8.3 million ton) nitrogen (N) and 2.3 million Mg (2.5 million ton) phosphorus (P). This compares to about 9 million Mg (10 million ton) N and 1.7 million Mg (1.8 million ton) P of fertilizer used in this country annually. Roughly half the annual manure produced in this country is produced in confinement and is recoverable. Because of the magnitude of animal wastes produced, the conservation and utilization of nutrients contained in these materials presents an enormous economic opportunity to provide nutrients for crop production. By increasing the efficiency of utilization of animal wastes, the quantity of nutrients leaking from these manures into and degrading the environment could significantly be reduced. Thus efficient utilization of animal manures not only reduces the need for purchased fertilizers, but also reduces their pollution potential.

In this chapter, manure production and utilization for the major species of farm animals are discussed, and associated problems are identified. Best management practices are outlined, and environmental and social consequences of current manure utilization practices are also presented. Finally, the needs and opportunities for research to address problems associated with present management systems are identified and discussed.

I. Beef Feedlot Manure Management

Summary

About two-thirds of the beef cattle feeding in the United States occurs in the states of Nebraska, Texas, Kansas, Iowa, and Colorado. Over 80% of the fed cattle are produced in feedlots of over 1000 head capacity. Manure produced by fed cattle, if all conserved and utilized, would provide 100 kg nitrogen (N) ha⁻¹ (89 lb. N a⁻¹) for 8.4% of the corn and wheat acreage in the nation. Nutrients excreted in beef feedlots would cost over \$ 461 million if purchased as fertilizer. However under present practices about 50% of this N is lost (primarily by runoff, ammonia volatilization, and denitrification) before removal from the feedlot. In addition, 50% of the N removed may be lost in the process of hauling, spreading, and incorporating into the soil. Phosphorus (P) losses are less because P is lost primarily through runoff. Because beef feeding is concentrated in the Central and Southern Great Plains where a high percentage of the land is cultivated, there is usually ample land area within economically acceptable distance on which to utilize manure. However, acceptable soil loading rates have not been well defined because of variability in manure composition, unpredictable mineralization rates, and lack of standards by which to define loading rates. Should these rates be based on

N or on P build-up in soils? Basic soil microbiological studies on the manure decomposition process are needed in order to predict the fate of nutrients in manure when land applied. Partially because of the geography of the beef fattening area, there is presently only limited opportunity for using manure for purposes other than land application. Besides problems associated with conservation of nutrients in manure before removal from feedlots (feedlot management problems) and in transporting and utilizing manure on crop land, a number of other problems are outlined. These include use of manure with no-tillage systems to achieve conservation compliance, environmental problems associated with composting, pollution from abandoned feedlots, salt build-up, and others. In addition to the need for some additional intensive research, an educational program is also needed to achieve the required technology transfer.

A. Introduction

When animals are grazing on pastures and rangelands, manure is dispersed across a large area and little management is needed because the material is not concentrated and decomposes on the soil. However, when animals are concentrated in a small area, the quantity of manure requiring management increases significantly. In the United States beef cattle feeding is concentrated in the Central and Southern Great Plains. Leading states in 1991 were Nebraska, Texas, Kansas, Iowa, and Colorado, which collectively fed two-thirds of the beef fed in 1989. Approximately 84% were fed in feedlots with capacity of 1000 or more head (Krause, 1991). Handling and utilizing the manure produced in these large feedlots is a significant environmental problem that must be addressed.

Manure from these confined animal feeding units is an important resource for crop production and soil sustainability because this manure is a source of macro nutrients (N, P and K) as well as minor nutrients (Zn, Mg, S, Na, Cu etc.). This manure can also be an excellent source of organic matter when added to soils, restoring some of the organic matter that has been depleted by present agricultural practices. However, manure produced by beef cattle can potentially be a source of water, air and land pollution. These products can pollute the surface and ground water with excess nitrates, salts, microorganisms, and pathogens. Production of greenhouse gases from the feed-

lots is another factor to consider when managing animal manure.

The purpose of this chapter is to review present practices and knowledge relating to beef cattle manure production and utilization. Emphasis is put on manure production in confined beef feedlots because, although this represents no more than one-third the total beef cattle population, problems related to manure management are much greater for feedlots than for pastures and ranges.

B. Manure Production And Composition

There were about 99 million head of cattle and calves in the United States in 1990 (Table 1). This is a reduction from the 102 million head in 1987 and 132 million head in 1975 (U.S. Dept. Agriculture, 1990). About 84 million of these cattle and calves are grown for beef production. If each animal excretes 56.2 kg (124 lb.) N and 16 kg (35.3 lb.) P annually, total production is about 4.72 and 1.34 million Mg (5.20 and 1.48 million ton) N and P respectively (Fedkiw, 1992). This is about 61 and 64% of all N and P excreted by all classes of livestock in the United States. However, about two thirds of these cattle and calves are normally on pasture or range, and the manure they produce cannot normally be collected and utilized elsewhere.

About 28 million head of cattle were fattened on grain and concentrates in the United

Table 1. Number of cattle and calves in the United States at different times.

Year ^a	Total	Beef cows	Milk cows	Bulls	Calves >227kg (500lb)	Calves <227 kg (500lb)	Cattle slaughtered	Calves slaughtered
-----million-----								
1975	132.0	45.7	11.2	3.0	35.8	36.3	41.5	5.4
1980	111.2	37.1	10.8	2.5	33.3	27.6	34.1	2.7
1985	109.7	35.4	10.8	2.4	34.7	26.4	36.6	3.4
1990	99.3	33.7	10.1	2.2	33.9	19.3	34.1	2.2

^a Data taken from U. S. Dept. Agriculture (1990).

States in 1987 (U. S. Dept. Commerce, 1987), of which 64% were concentrated in the Great Plains area compared to 58% in 1982. At any one time, there are at least 10 million head of beef cattle on feed (Table 2), and they excrete approximately 145 g (0.32 lb.) of N in fresh manure daily per head (Overcash et al., 1983a). After collecting the manure from the feedlot, however, the N produced per head per day is 124.9 g (0.28 lb.). Thus, these cattle excrete approximately 457900 Mg (505000 tons) of N annually in their manure. Comparable values for phosphorus (P) and potassium (K), based on 42.7 g (0.09 lb.) P and 131.5 g (0.29 lb.) K excreted per head per day (Overcash et al., 1983a), would be 157000 Mg (173000 tons) P and 482000 Mg (531000 tons) K. If purchased as fertilizer, the value of the N, P, and K in this manure would be approximately \$111, 180 and 170 million for N, P, and K, respectively, for a total value of

\$ 461 million annually. This does not include the value of the minor elements in beef feedlot manure. At a rate of 100 kg N ha⁻¹ (89 lb. N ha⁻¹), beef feedlot manure contains enough N to fertilize almost 4.6 million ha (11.4 million acres) of grain crops, or 8.4% of the corn and wheat acreage in the United States.

For the approximately 54 million head of beef cattle on pastures and range, their manure is dispersed across a large area. This manure is not normally collected and usually does not constitute an animal waste management problem. The effect of this manure on the environment is also minimal since the dispersed manure will be decomposed on the soil. Overgrazing of pasture lands and rangelands, however, can be a potential problem by creating soil erosion and loss of riparian vegetation and causing surface water contamination by manure.

Several factors that may affect mineral composition of animal manure are animal size and species, housing and rearing management, ration fed, manure storage, and climate. Typical nutrient concentrations for beef feedlot manure are given in Table 3. Nitrogen contents of beef manure were 3.1, 4.2, 2.7, and 1.9 % of total solids when collected from scraping under slotted floors, in pits or tanks, bedded units, and feedlots, respectively (Overcash et al., 1983a). Fresh and scrapped beef manure had P contents of 1.1 and 0.7% of dry weight, and K contents of 2.5 and 2.0%, respectively (Westerman et al., 1985). Nitrogen content of urine and feces increased with increasing N intake (Overcash et al., 1983b). Nitrogen is often lost by ammonia volatilization from stored manure. However, losses are highly variable (0 to over 50%), and depend on a number of factors including type of storage.

Phosphorus is usually contained in the feces and only trace amounts are excreted in the urine while most of the K excreted in cattle manure is in the urine. About 96% of P is in feces while 73% of K is in urine (Safley et al., 1985). About 58% of N is also in the urine, most of it as urea (Overcash et al., 1983a). Total P, K, Ca, Mg, and Na contents of fresh beef manure were 1.1, 2.4, 1.5, 0.55, and 0.46% of total solids, respectively (Over-

Table 2. Annual manure, N, P, and K excreted by feedlot beef cattle in the United States and major producing states.

State	No. of animals	Manure ^b	N	P	K	N Value ^c
		million million Mg	million Mg	million Mg	million Mg	million \$
U.S.A	10.06	24.1	457.9	156.7	482	111.4
California	0.39	0.94	17.9	6.11	8.8	4.4
Colorado	0.90	2.16	41.0	14.0	43.2	10.0
Illinois	0.30	0.72	13.7	4.7	14.4	3.3
Iowa	1.02	2.45	46.6	15.9	49.0	11.3
Kansas	1.70	4.08	77.5	26.5	81.6	18.8
Minnesota	0.33	0.79	15.0	5.1	15.8	3.6
Nebraska	2.15	5.16	98.0	33.5	103.2	23.8
Oklahoma	0.32	0.77	14.6	5.0	15.4	3.6
So. Dakota	0.27	0.65	12.4	4.2	13.0	3.0
Texas	2.11	5.06	96.1	32.9	101.2	23.4

^aU.S. Department of Agriculture (1990)

^bBased on 2.4 Mg total solid per animal per year in the feedlot and which contains 1.9, 0.65, and 2.0% N, P, and K, respectively (Overcash et al., 1983a).

^cBased on \$ 243.2 per Mg N.

cash et al., 1983a). In the feedlot, these percentages were 0.65, 2.0, 1.3, 0.69, and 0.74 %, respectively. Nutrient concentrations (in mg kg⁻¹) were 5600 Fe, 78 Zn, 18 Cu, 380 Mn, 140 B, 14000 Cl, 5000 S, 1.7 Cd, 5200 Al, 9 Li, and 1.9 Pb of the dry solids in the feedlot (Table 3). The main form of N in fresh cattle feces is organic bound N. Fresh cattle manure also contains urea and small amounts of ammonium N (Kirchmann and Witter, 1992). Fresh manure from a 454 kg (1000 lb.) beef animal contained 37% urine (Overcash et al., 1983b).

Table 3. Dry solid nutrient concentration in beef feedlot manure.

Nutrient	Concentration*	
	Range	Average
	%	
N	0.55 - 4.00	1.90
P	0.12 - 1.60	0.65
K	0.29 - 3.20	2.00
Ca	0.17 - 3.60	1.30
Mg	0.19 - 1.50	0.69
Na	0.10 - 2.80	0.74
Fe	0.12 - 1.25	0.56
Zn	0.001 - 0.014	0.008
Cu	0.0001 - 0.003	0.002
Mn	0.006 - 0.115	0.038
B	0.014	0.014
Cl	1.4	1.4
S	0.5	0.5
Cd	0.0002	0.0002
Al	0.52	0.52
Li	0.0009	0.0009
Pb	0.0002	0.0002

*Data from Overcash et al. (1983a)

C. Manure Management Systems

Approximately 84% of the beef cattle fattened in 1989 were fed in lots with over 1000 head capacity, and 50% in lots with greater

than 16000 head capacity (Fedkiw, 1992). Because of this concentration, manure management and availability of land for its application are important factors to consider. Manure management guidelines must consider the following factors: (A) the effects of different management systems on nutrient content of manure at the time of spreading; (B) the effects of changes in manure spreading and incorporation methods on nutrient availability; (C) methods to assist farmers in determining application rates to achieve a desired crop yield; (D) safeguards to insure that application rate will not cause undue losses of N and other nutrient to surface and ground water (Bulley et al, 1980).

Beef feedlot manure contains considerable amounts of nutrients which can be utilized for crop production. Nutrient loss, specifically N, in storage, during handling, and after application, is a major problem in effectively utilizing this resource. Up to 50% or more of the N in fresh livestock manure may be in ammonium form or be converted to ammonium form in a very short time following excretion, and is therefore subject to volatilization loss (Vanderholm, 1975). In a laboratory study simulating cattle feedlot surface conditions, Stewart (1970) found N losses from urine to be 25-90%, largely due to ammonia volatilization. Adriano et al. (1971) found nearly 50% of total N to be lost on simulated feedlot surfaces, which was consistent with their 40% loss in the field from corral surfaces. In studying solid waste from feedlot surfaces, Gilbertson et al. (1971) recovered 42 to 55% of estimated excreted N, indicating that the rest was lost. Losses of N from the feedlot are primarily through runoff or gaseous emissions (NH₃ volatilization and denitrification).

Most beef feeding occurs in confined open lots, with only a small percentage occurring in closed housing. Manure normally accumulates in the pens of beef feedlots until animals in a pen are marketed (usually 90 to 180 days on feed) or once each year. Also because a high percentage of the beef cattle are fed in drier climates, the mechanisms by which nutrients are lost from beef feedlots are much different than those for confined housing operations, especially those in which water is used to flush manure into pits for stor-

age. Typically in the Central and Southern Great Plains, beef feedlot manure is scraped from feedlots, mixing as much as 50% soil with the manure. This manure is then stockpiled until fall. Spreading on cropland normally occurs after harvest in the fall or in early spring before crops are planted.

Using the system outlined above, often over 50% of the N excreted in the manure is lost before removal from the feedlots (Overcash, et al., 1983b; Gilbertson, et al., 1979b). For example in Nebraska, Gilbertson et al. (1971) found that 80% of the N fed to beef cattle was excreted in the manure, but only 48% of the N excreted was removed as manure when the lots were cleaned (39% of the N fed was removed). For dairy barn lots, Safely et al. (1986) measured N, P, and K losses of 23, 0 and 10%, respectively. Depending upon how the manure is handled and field applied, as much as 50% of the N remaining in the manure after removing from feeding pens may be lost by the time the manure is spread and incorporated. Thus often only a fraction (~ 25%) of the N excreted in beef feedlot manure is utilized in the field by the growing crop. Therefore there is tremendous opportunity to improve the efficiency of recovery and utilization of the N in this manure.

Several practices might be employed to reduce N losses from the manure deposited during the feeding operation. These might include more frequent cleaning, use of bedding, and use of additives to reduce volatilization and denitrification losses of N. These could include such materials as nitrification inhibitors, urease inhibitors, acidifying materials (phosphoric acid, pyrite, ferrous sulfate, sulfur), and precipitants or stabilizers such as alum, quick lime, or cement kiln dust. Although there have been a few studies using some of these materials on poultry or swine manure, essentially no comprehensive research has been conducted for beef cattle feedlot manure.

Temperature, moisture, pH, and C/N ratio are important factors in determining the amount of N lost from manure. Muck and Richards (1983) concluded that little N may be lost with daily temperature below 5 °C, but 40 to 60% of total manure N can be lost through ammonia volatilization at tempera-

tures between 5 °C and 25 °C. Adriano et al. (1974) found that at 10 °C, average losses of N from cattle manure were 26 and 39% at 60 and 90% moisture levels, respectively. At 25 °C, however, 40 and 45% N losses were observed for the 60 and 90% moisture levels, respectively. Manure application rate did not have a significant effect on the percentage of N lost. In large soil columns, Peters and Reddell (1976) found a 10% loss of total N at a soil pH of 7.5 and 20% loss at a soil pH of 12 when manure was mixed with soil and incubated for 30, 60 and 90 days (average of the three). Stevenson and Wagner (1970) stated that losses of N as free ammonia are particularly serious on calcareous soils. Webber and Lane (1969) reported that a soil pH 8.0 is favorable for ammonia volatilization.

A wide C/N ratio may reduce volatilization loss of N. Bedding, in addition to its absorption properties, helps reduce volatilization losses of N during drying by immobilizing more N. However, use of bedding results in a reduction of manure N availability due to a wide C/N ratio (Hensler et al., 1970). These researchers also concluded that when manure was applied to corn, total dry matter of corn was not affected by increasing amounts of bedding up to 8%, but at the 16% rate, yields were usually less than for manure with no bedding.

Composting manure is a useful method of producing a stabilized product that can be stored or spread with little odor or fly breeding potential (Sweeten, 1988). Other advantages of composting include killing pathogens and weed seeds, and improving handling characteristics of manure by reducing its volume and weight (Willson and Hummel, 1975). Decomposition of manure occurs through biological action and spontaneous chemical reactions. The initial chemical and biological composition of manure is a function of ration fed, animal age, bedding, and other factors which can influence the decomposition process. In a constant temperature/humidity chamber, ammonia volatilization from beef cattle manure resulted in a 35% decrease in N content of the material during composting (Stone et al., 1975). In the compost, ammonia was only 3 to 4% of the total N and 0.05 to 0.1% of the dry matter. The greatest change in am-

monia concentration occurred at 48.8 °C and 70% moisture. Wells et al. (1969) also showed that N is lost as ammonia during composting. Martin et al. (1972) indicated that widening the C/N ratio of the waste decreases the amount of N lost during composting. Loehr (1974), however, stated that composting conserves much of the nutrient content, including N. Compared to fresh manure, three-month stabilized farmyard manure had significantly greater concentrations of total N, water soluble substances, and lignin, and less organic C, lipid, and hemicellulose, as well as a lower C/N ratio (Levi-Minzi et al., 1986).

Nitrogen loss during composting depends on the conditions under which the material is being decomposed. Willson and Hummel (1975) found that while moisture content, pH, and material bulk have little effect on N loss, periods of anaerobic activity during composting may increase N loss. Since N losses are less than the reduction in volatile solids due to biooxidation, N concentration during composting usually increases. Nitrogen can also be lost from manure in runoff and by nitrate leaching during composting. Quantity of N lost by these processes are controlled mainly by site-specific conditions.

Composted manure can be applied to soil as an odorless and drier source of nutrients as compared to non-composted manure. In addition, Kirchmann (1990) found that applying composted poultry manure to soil caused a larger uptake of soil N than fresh manure. Composted manure with low available energy caused a positive apparent added N interaction, while energy-rich fresh manure caused a negative added N interaction and subsequently, a lower soil N uptake.

The amount of manure to be applied to a particular soil depends on crop requirements for N and P, composition of the manure, and environmental conditions. Manure applications to provide adequate N for crops may result in soil build-up of salt, P, K, and other ions in areas where rainfall is limited. Manure application rates may best be based on P needs of a crop, with additional N supplied by fertilizer, in order to avoid adverse environmental consequences, especially nitrate leach-

ing and runoff losses, as well as high P levels in runoff.

Manure nutrient loss after soil application depends on degree of incorporation and environmental conditions. In laboratory and field experiments, Steenhuis et al. (1981) showed that most N loss from manure spread on frozen soil was in water soluble forms (mainly nitrate and ammonium N). The first melt water contained the highest concentration of readily available N. Dairy manure applied at 35, 100, and 200 Mg ha⁻¹ in 1972 resulted in average run-off loss of 16, 1, and 0.2 kg inorganic N ha⁻¹ in 1972, 1973, and 1974, respectively (Klausner et al., 1976).. Phosphorus loss during these 3 years were 3.5, 0.7, and 0.01 kg ha⁻¹, respectively.

D. Land Application Of Manure

There were about 390 million hectare (about 1 billion acre) of land in farms in the United States in 1990, of which 134 million ha (330 million acre) were cropland and 265 million ha (650 million acre) were pasture and range land (U.S. Dept. Agriculture, 1990). Nationally this provides an ample base for land application of animal manure. Based on 1982 statistics, EPA estimated that in only 28 counties in the nation did the ratio of animals to cultivated acreage indicate a serious manure utilization problem (Fedkiw, 1992). Most of these counties were in coastal states where few beef cattle are produced. Other potential uses of manure are land filling, burning, converting to methane, and refeeding. However, for beef cattle feedlot manure, particularly when produced in the Central and Southern Great Plains, these other options offer limited opportunity for manure utilization. Factors to consider for land application of manure are transportation and spreading equipment problems and related costs, land base available, problems in collecting a representative manure sample for nutrient analysis, and application rates that provide the crop with sufficient nutrients without having adverse effects on the environment.

Transport of animal manure to the application site is an important part of any management system. Manure can be in solid, slurry, or liquid (<5% dry matter) form with each requiring a different management practice. Beef feedlot manure, valued for its N and P nutrient content, is an economical substitute for commercial fertilizer. Freeze and Sommerfeldt (1985) found that manure from large farm-feedlots, which haul manure less frequently and use a farm tractor with front-end loader and single axle truck with a manure box, can haul manure up to about 15 km (9.4 miles) and recover all costs by the value of nutrients in the manure. For the small farm-feedlots employing a farm tractor with front-end loader and pull-type manure spreader, manure can also be economically hauled up to 15 km (9.4 miles) if non-cash costs and labor charges are disregarded (Freeze and Sommerfeldt, 1985). Fortunately, in the area of the United States where most beef cattle are fed (Iowa to Colorado to Texas), most of the land is under cultivation, so there is seldom a shortage of available farmland for application of manure. If an animal excretes 145 g (0.32 lb..) N per day, this would provide about 53 kg (116 lb..) N per year, about enough to fertilize 0.3 ha (0.7 acre) of irrigated corn, if 100% effective and with no losses. Thus a 10000 head feedlot could utilize all its manure on 3000 ha, or within a radius of about 3 km (1.8 mi) of the feedlot, and a 50000 head feedlot requires 15000 ha, found within a radius of about 7 km (4.2 mi) of the feedlot.

Manure spreaders are the most typical method of transporting and spreading animal wastes with moisture contents <80% (Overcash, et al., 1983b). These spreaders can be either box type or of the open tank design. Box spreaders can be pull-type or truck mounted. Slurries may be transported with either a mobile tank or by pipeline. Some agitation is necessary before removing liquid material from storage areas or pits. Liquid waste with hydraulic behavior like water is normally transported in tanks, although this is more expensive than using irrigation equipment. The liquid wastes can be applied with surface (furrow, flooding or border) irrigation but better distribution can be obtained by sprinkler irrigation, traveling gun or center pivot system.

Solid beef manure, slurries and liquids can be either surface applied or incorporated into the soil. Applying animal manure below the soil surface has advantages of preventing an unsightly appearance to the field, less odor and fly problems, reduced volatilization and runoff losses, and generally better conservation of nutrients for use by crops (Barlett and Marriott, 1971). Large bore irrigation nozzles can be utilized on sprinkler irrigation systems to handle slurries as well as liquid wastes.

Recent farm legislation in the United States requires producers to protect highly erodible soils from erosion. Therefore, when crop residues are sparse, it may not be possible to incorporate manure and still meet conservation compliance requirements. Unfortunately there have been few experiments conducted utilizing beef feedlot manure under no-tillage cropping systems, but considerable ammonia would probably be lost by volatilization because of lack of incorporation.

Effective utilization of manure and determining the best agronomic rates of application depend on proper sampling of the manure. Animal manure is highly variable in nutrient content. Therefore, collecting a representative sample is essential so that the manure can be analyzed and proper application rates determined. Manure applied in excess of the crop needs for any nutrient can contribute to surface and ground water contamination. Soil sampling should be done prior to manure application to assess the nutrient need of the crop and to determine the proper application rate based on manure nutrient content. Because plant availability and crop uptake of nutrients in manure are affected by many variables, it is usually desirable to adhere to Extension Service recommendations in each state to determine proper application rate. Gilbertson et al. (1979b) estimated that on the average, about 35% of the N and 20% of the P in beef manure was utilized the first year after application to a corn crop, but these values can range widely depending on conditions.

E. Alternative Utilization Of Beef Feedlot Manure

Cattle manure has been used for algae and fish production in lagoons, reclamation of sandy and mined soils, recovery of energy by anaerobic methane gas production, and for re-feeding (Umstadter, 1980). Anaerobic bacterial decomposition of cattle manure can be utilized to generate methane gas which can be collected and used for various purposes. About one third of the defecated manure nitrogen could be utilized in animal refeeding depending on the type of manure and type of animal consuming the manures (Overcash, 1983b). Other alternative uses of manure are pyrolysis, hydrogasification, oil conversion process, composting and fish farming. Pyrolysis is pretreatment of animal manure by thermochemical processes in a closed system at elevated temperatures of 204 to 800 °C (400-1472 °F). This process provides a solid fraction termed char, a gas fraction which when condensed is an oil or fuel, and a gas fraction which when condensed is aqueous in nature. In the hydrogasification process, cellulose in the presence of hydrogen under high pressure and temperature is partially converted to a gas rich in methane. A process similar to liquidification of coal can be used to convert manure to an oil-like product.

Composting is the aerobic treatment of manure in the thermophilic temperature range (40-65°C, 104-149°F). The composted material is an odorless, fine textured, low moisture content material that can then be bagged and sold for use in gardens, potting, and nurseries or used as fertilizer. The heat generated during composting can also be harvested.

Although there are a number of potential uses for beef feedlot manure, in practice only a small fraction is used for purposes other than land application. Part of this probably results from the fact that most of the beef cattle manure is produced in agricultural regions where demand for other products (methane gas, energy, etc.) is better provided by other sources. Although this manure, when proc-

essed, is an acceptable feed for poultry, distance between concentrated beef feeding and poultry production centers is generally too great for this practice to be economical.

Use of manure in aquaculture, practiced for centuries in the Far East, is a useful method of utilizing the resources in the manure. Wohlfarth and Schroeder (1979) found that maximum yields per unit area are higher with high-protein feeds than with manure, but at a greater cost. Best results were obtained in fish ponds by frequent applications of manure. Incorporating manure into high-protein feeds resulted in reduced growth and failed to reduce feed cost per unit area.

F. Agronomic And Environmental Effects

Beef cattle manure, which is a valuable resource because of its nutrient and organic matter contents, can be effectively utilized for crop production and soil improvement. Manure contains N, P, K and other micro nutrients which are necessary for plant growth. Organic matter, which is an ion exchange material, chelating agent, buffering material, and an important agent in soil aggregation, can also be increased in soils by manure addition. Total organic carbon, Kjeldhal N, and potentially mineralizable N in manure-amended surface soils (0-7.5 cm, 0-3 inch) were 22 to 40% greater than in nonmanured soils receiving fertilizer and/or herbicide (Fraser et al., 1988). Application of cattle feedlot manure significantly increased soil organic matter and total N and lowered the C/N ratio of the surface 30 cm (12 inch) soil (Sommerfeldt et al., 1988). Soil organic matter, available P, and exchangeable K, Ca, and Mg increased on a loam and a sandy loam soil with increasing rates of manure application (Vitosh et al., 1973).

Manure application can improve soil physical properties such as infiltration, aggregation, and bulk density, which in turn result in reduced run-off, wind and water erosion. Manure also decreases energy needed for tillage, and reduces impedance to seedling emergence and root penetration. Increased soil

aggregation and subsequent soil water infiltration resulting from manure application has frequently been documented (Mielke and Mazurak, 1976; Boyle et al., 1989). However, excess manure application may have adverse consequences. In addition to increased potential for surface and ground water pollution, excess manure application may increase soil electrical conductivity and sodium adsorption ratio (SAR), and decrease soil pH (Chang et al., 1991). Increased SAR may reduce soil water infiltration rates.

Conservation of nutrients in storage and during handling and more timely incorporation of manure to conserve N and other nutrients could reduce the cost of crop production. These practices offer the commercial crop-livestock producer an opportunity to achieve a greater degree of self-sufficiency in plant nutrients, as well as economic and energy efficiency (Stonehouse and Narayanan, 1984). When farm yard manure was priced on the basis of its total N and P contents, net return for applications of 11 and 22 tons ha^{-1} manure averaged \$ 48 and \$ 100 ha^{-1} (Holt and Zentner, 1985).

Beef cattle manure application can increase the yield of most crops. In a number of published results, yield of corn silage, corn grain, grain sorghum, forage sorghum, and perennial forage crops were increased with applications of cattle manure or manure effluents (Magdoff and Amadon, 1980; Swanson et al., 1974; Sukovaty et al., 1974; Mathers et al., 1975). Manures, if properly handled, are a good substitute for fertilizers as a source of nutrients, and have the added benefit of improving soil physical characteristics.

Manure should be managed and applied at rates that do not adversely affect the environment. Manure applications supplying available N in excess of crop requirements can be a potential source of ground water contamination. For grass swards grown on a deep well drained soil, manure supplying total N at the rate of approximately two times the crop requirements for N, contributed nitrate-N to the ground water (Marriott and Bartlett, 1975). Plots treated with 22, 45, 112 and 224 Mg of manure ha^{-1} had nitrate-N amounts ranging from 100 to 2400 kg ha^{-1} (89 to 2143 lb.

acre^{-1}) in the top 1.8 m (6 feet) of soil (Mathers et al., 1975). Deep rooted crops can be used to extract nitrate-N from soil depths greater than that for the root zone of most annual crops (usually 1 to 1.5 m). Alfalfa grown on heavily manured plots removed water and nitrate-N to a depth of 1.8 m (300 kg N ha^{-1}) the first year and to 3.6 m the second year. Schuman and Elliott (1978) also reported significant removal of nitrate-N by alfalfa from an abandoned feedlot area with elevated nitrate concentration (2000 kg N ha^{-1}) in a 4.6 m soil profile. Corn was not as effective as alfalfa in removing nitrate-N and contained too much nitrate in the forage to be safely utilized by livestock (Schuman and Elliott, 1978).

High rates of manure application will cause a significant build-up of N, other nutrients, and salt in the soil. Large applications of manure (22.4 Mg ha^{-1}) can also cause a significant build-up of soil exchangeable K and extractable P (Vitosh et al., 1973). Bray and Kurtz no. 1 P soil test values increased linearly from 45 to 391 mg kg^{-1} with manure applications of 0 to 361 Mg ha^{-1} (Vivekanandan and Fixen, 1990). These high soil P levels could have adverse effects on the availability of some minor elements. In areas with heavy rainfall and natural leaching, salinity build up from manure application is not a major problem; however, in irrigated and low-rainfall areas, application of materials containing salt must be limited to prevent salt accumulation (Gilbertson et al., 1979b). The amount of NaCl salt in the beef ration directly affects Na concentration in the manure, which in turn affects the exchangeable Na and SAR in soil (Horton et al., 1975). Sodium accumulation results in soil dispersion and greatly reduces infiltration. The quantity of NaCl in rations today is considerably less than 20 years ago, so the problem is less acute than it was when much of the reported research were conducted.

Manure in the feedlot can be a source of pollution. Nitrate-N in abandoned feedlots averaged 7200 kg ha^{-1} (6428 lb acre^{-1}) in a 9.1 m (30 feet) soil profile, while adjacent cropland had only 570 kg ha^{-1} $\text{NO}_3\text{-N}$ in the same soil depth (Mielke and Ellis, 1976). Abandoned feedlots with as much as 18200 kg ha^{-1} in a 9.1 m soil core were identified. However, Ellis et al. (1975) took soil cores from 15 ac-

tive eastern Nebraska beef cattle feedlots and showed that most did not constitute a nitrate pollution hazard to ground water. In active feedlots, compaction from hoof action coupled with NaCl in the manure result in essentially no water infiltration or leaching (Mielke and Mazurak, 1976). Hence there is little accumulation of nitrates in the subsoil (Lorimor et al., 1972). Mechanical removal of manure from feedlots also reduced opportunity for nitrate movement into the soil, helped to maintain the surface of the feedlot in an aerobic condition and minimized odor.

Cattle feedlot runoff is a source of pollution of surface waters. The pollutants include chemicals, microorganisms, organic materials, and soil sediments. Proper assessment of the pollution potential depends not only on the size, stocking rate, and other physical characteristics of the feedlot, but also on the intensity, duration and frequency of rainfall (Swanson et al., 1971). During a rainfall event, runoff will begin sooner from a feedlot than from an adjacent cropland because of the lower infiltration rate in a feedlot. Ammonium and nitrate-N are transported in the initial runoff from the feedlot surface and add to the surface water pollution problem (Swanson et al., 1975). Under Nebraska conditions, typically only 3 to 6% of the manure deposited in a feedlot is removed in runoff (Gilbertson et al., 1979a). Erosion in the feedlot depends on the land slope, slope length, infiltration rate and physical properties of the soil. Methods of surface water control have been developed for feedlots to reduce or collect the runoff water, such as terracing, check dams or porous dams, settling basins, tiled infiltration beds, lagoons, and vegetative filters. Constructed wetlands are also used, employing vegetative filters to remove solids and some soluble nutrients before runoff water is impounded in a shallow basin.

Runoff loss also occurs from the fields receiving manure and contributes to the pollution in surface waters. Amount of runoff is influenced by time, rate, and method of application, and by soil and cropping management practices (Khaleel et al., 1980). Application of manure to frozen soils often results in the loss of organic bound N and P with snow melt runoff. High nutrient loss may also result from

runoff events occurring shortly after application. Therefore, it is best to apply manure when runoff events are least likely. Incorporation of manure after application reduces runoff loss, conserves manure nutrients and improves soil physical properties as compared to surface application. Amount of runoff loss increases with increasing rate of application. Patni et al. (1975) found no consistent differences in bacterial quality of runoff from manured and non-manured fields when the manure had been incorporated.

Manure is also a source of air pollution because several gases are formed and volatilized during decomposition. Considerable dust may also be added to the air. Gases such as carbon dioxide, methane, ammonia, and nitrous oxides, and hydrogen sulfides may contribute to the greenhouse effects (warming of the atmosphere by trapping of heat). The magnitude of the contribution of these gases to global warming is not known. Ammonia is readily volatilized from the urea in urine and often increases atmospheric NH_3 concentrations several fold near feedlots (Elliott et al., 1971). However, ammonia is readily washed back into the soil by precipitation so air contamination is usually local. Nitrous oxides escape to the atmosphere when nitrates are denitrified, usually under wet conditions such as rain-soaked feedlots. Nitrous oxides can be a major contributor to the greenhouse gases. Unfortunately essentially no data is available to quantify the amount of nitrous oxides emitted from beef cattle feedlots annually.

G. Issues And Options

Education is the key to a proper animal manure management system. Water quality protection, particularly from non-point sources or unregulated point sources, is one of the issues that needs to be addressed by increased research, technology transfer, public policy initiatives, and private action on the part of the producers (Sweeten, 1992). Other issues include air quality protection, emissions of greenhouse gases, land and soil sustainability, animal welfare, water use, societal and producer's benefits from animal manure, recovering energy from animal manure, effects of pollution from animal manure on the

animal themselves, and ability of livestock to convert non-edible plants into human food products (Sweeten, 1992).

Point sources of water pollution from livestock can be minimized or eliminated by use of proper management systems which include selection of appropriate sites for concentrated animal feeding operations, proper design of manure storage areas, waste water collection and application to croplands, and applying non-excessive rates of manure to croplands. Air quality impacts of animal manure can be lessened by aeration, anaerobic digestion, composting, and capturing the odorless and odorous gases. However, to accomplish all of this in the diverse settings in which feedlots are located, a major research effort is required.

Government regulations can greatly alter the management system employed for a beef cattle production operation. The federal regulatory approach to animal manure management emerged in the early 1970's as the U. S. Environmental Protection Agency (EPA) initiated its regulatory programs to implement the goals of the Clean Water Act of 1972 (Fedkiw, 1992). EPA regulatory efforts initially focused on point sources of pollution which were mainly effluents and solids from urban and industrial areas. Agriculture was largely seen as a non-point source of pollution. However, animal manure from concentrated animal feeding operations (CAFOs) were an exception in this regard and in 1973, EPA identified feedlots as point sources of pollution and therefore required the issuing of National Pollutant Discharge Elimination System (NPDES) permits (Fedkiw, 1992). CAFOs included operations where more than 1000 animal units (cattle or equivalent for poultry and other animals) are confined and fed for at least 45 days, and where pollutants are discharged following storms smaller than a 25-year, 24-hour storm event. Medium-sized feedlots with 300 to 1000 animal units that discharge pollutants directly into navigable waters through a human made conveyance or into waters that come into contact with the area used by such CAFOs were also made subject to NPDES permits. Operations not meeting these criteria were classed as non-point sources and were not subject to NPDES per-

mits. Land application of animal manure was also considered a non-point source and was not subject to NPDES permits. Non-point sources of pollution became the target of USDA and State Voluntary programs for improved animal manure management (Fedkiw, 1992). State regulatory approaches are basically consistent with NPDES requirements but vary between states. This allows regulations to vary depending on differences in climate, rainfall amounts and the number and mix of livestock.

Best management practices are essential for the effective utilization of beef cattle manure for crop production and pollution prevention. Nutrient conservation is the first step toward a best management system. Nitrogen is the most susceptible nutrient to loss by volatilization and leaching, and subsequently, should be conserved as much as possible. Factors that affect N loss include temperature, moisture, pH, aeration status, rainfall and C/N ratio. These factors should be considered when planning the utilization of animal manure. Most other nutrients (P, K, Ca etc.) are lost only through runoff and erosion of organic material. Reducing erosion and controlling runoff will considerably reduce the loss of all nutrients. In addition, proper rate and method of manure application can greatly improve soil sustainability and crop production without having adverse effects on the environment. Manure should be applied at a rate that provides adequate but not excessive nutrients to the crop. Incorporation of manure after application greatly reduces nutrient volatilization and runoff loss. Where incorporation is not possible because of the increased soil erosion hazard from incorporation, ammonia volatilization will probably be greater, but there is essentially no long term research to evaluate overall effects.

Beef cattle manure can be effectively and economically utilized by crops if a proper land base area is available to the feeding operation. Manure can be an economical substitute for commercial fertilizers when it is transported no more than about 15 km (9.4 miles) from the source (Freeze and Sommerfeldt, 1985). Because most of the major beef feeding operations in the United States are located in rural areas away from centers of

population, there are relatively few incidence of problems with odors or fly populations which are of major concern.

H. Needs

When considering beef feedlot manure as potentially a major source of N for the crops produced in the United States, several facts are apparent. Present feedlot management systems result in about a 50% loss of N from the manure before it is removed from the feedlot. In addition, another 25% of the N excreted in the feedlot may be lost as the manure is hauled, spread, and incorporated into the soil. Thus, often only about 25% of this resource is utilized. Consequently, considerable additional research is needed to develop practical feedlot and manure management practices that will reduce these losses of N to the environment. This approach would also reduce the magnitude of environmental damage that is now associated with beef feedlot operations.

We presently have some evidence that several changes in feedlot management may have some potential for reducing N losses from manure. These include such practices as frequent cleaning, use of carbonaceous bedding (straw, cornstalks, paper), inhibitors (nitrification and urea hydrolysis processes), and various types of stabilizers (acids or acidic materials, quick lime, alum, etc.). However, considerable research remains to be conducted to determine what the benefits from these practices might be and which would be most practical and economical.

For land application of feedlot manure, we have many unanswered questions and problems. Suitable methodology is lacking for making rapid and economically acceptable field determinations of the nutrient content of manure. This is a necessary step in calculating acceptable rates of application. Also we lack dependable and practical equipment to accurately spread manure on soils at the desired rates. We need considerably more research and new models by which the best rate of application can be determined for a given situation. In order to achieve this, considerable basic research on the soil microbiology associ-

ated with manure decomposition is needed to accurately predict availability and release rates of nutrients in manure. We will also need to know how these processes are affected by climatic conditions at those times of the year when it is practical to apply manure. In addition, better evaluation of the effects of manure on minor element concentrations and availability in different soils is needed, and we need to define acceptable upper limits for enhanced soil P availability resulting from repeated manure application.

It is known that manure application results in changes in soil aggregation and tilth, which in turn affect soil, water, and air relationships. It is also known that changes in soil, water, and air relationships affect microbial activity. However, in order to better define these changes and quantify relationships that exist between all these factors, we need greatly improved technology for characterizing these properties and parameters. These all relate to potential losses of nutrients from the soil by leaching, runoff, volatilization, or denitrification. We have very little information with which to quantify denitrification losses.

Several other problems associated with feedlot management are in need of additional research. These include the management of under-stocked or abandoned feedlots where the potential for nitrate leaching is great. Possibly by adding soluble C, such as alcohol, nitrate in these sites could be denitrified. Also as was pointed out in earlier discussion in this section, we need to develop technology whereby manure can be used with no-tillage systems to maintain residues on the soil surface for erosion control. Likewise, especially in drier regions, we still need to establish soil loading rates that will prevent undesirable salt build-up. The circulation, amounts and effects of ammonia gas in the atmosphere near feedlots also requires more study.

One could continue for some length on this list of information needed for improved management of beef feedlot manure. The paramount problem, as stated earlier, is to develop methodology whereby one can greatly reduce the loss of nutrients (especially N) from manure into the environment. If these losses are

substantially reduced, many of the other factors listed above will be at least partially addressed.

Complementary to such a research program as outlined above, a corresponding technology transfer program is needed to get the information into the hands of the users. This will require some detailed economic analyses of different situations, which can probably be best addressed through the development of suitable computer models. It is disheartening to see how little use is presently being made of the information that is available, much of which was published 15 to 25 years ago.

Recommendations:

Developing practical feedlot and manure management practices that would reduce losses of N or other nutrients to the environment.

Determining the benefits from using additives to feedlots to prevent N losses.

Developing suitable methodology for making rapid and economically acceptable field determinations of the nutrient content of manure for calculating acceptable application rates.

Producing dependable and practical equipment to accurately spread manure.

Developing models by which the best rate of application for a given situation can be determined.

Conducting basic research on soil microbiology associated with manure decomposition to accurately predict availability and release rate of nutrients in manure.

Better evaluation of the effects of manure on minor element concentration and availability in different soils is needed.

Define acceptable upper limits for available soil P resulting from repeated manure application.

Improving technology for characterizing effects of manure on soil aggregation and tilth, microbial activity, and soil water, and air relationships.

Better quantification of denitrification losses of N.

Management of under-stocked and abandoned feedlots to prevent nitrate leaching.

Determining the effects of manure as soil cover in no-tillage systems.

Establishing the desirable manure loading rates in drier areas to prevent salt build-up.

Developing technology transfer to get the information into the hands of the users.

Developing computer models with economical analysis of costs and benefits of manure utilization to be used by the growers

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II. Poultry Manure Management

Executive Summary

Increases in the demand for poultry products have led to rapid and concentrated growth of the industry, which has caused problems with manure utilization in certain areas. Although poultry litter is one of the best organic fertilizers available, excessive land application rates can lead to nitrate leaching into groundwater, phosphorus (P) runoff into adjacent water bodies and possibly cause elevated bacterial or viral pathogen levels in lakes and rivers. Approximately 13 million Mg of litter and manure was produced on U.S. poultry farms in 1990, most of which (68%) was broiler litter. Except for small amounts used in animal feed, the major portion (90%) of poultry manure produced is applied to agricultural land.

Adverse impacts resulting from land application of poultry manure may be prevented by implementation of effective best management practices (BMPs). Examples of BMPs include use of buffer zones between treated areas and waterways, correct timing and placement of manure, nutrient management, and irrigation scheduling of liquid manure to limit ground water contamination. These practices manipulate the soil system to minimize pollutant loss to surface or ground water.

Future research needs include the development of new BMPs which result in decreased negative environmental impact from land applications of this important resource. These should include practices which decrease ammonia volatilization, leaching of nitrate, P runoff and pathogen release. Research to determine whether to base litter loading rates on N or P would also be beneficial.

A. Introduction

Increases in poultry production in recent years, fueled by the demand for low-cholesterol meat products, have led to tremendous expansion in the industry. However, rapid and concentrated growth of the poultry industry in several states has caused increasing concern about the disposal of poultry wastes with respect to non-point source pollution. Although poultry litter is one of the best organic fertilizer sources available, excessive applications of litter (as with any fertilizer source) can cause environmental problems. Nitrate leaching into the groundwater, non-point source phosphorus runoff into surface water bodies and release of pathogenic micro-organisms are three of the main problems encountered with improper management of this resource. The objective of this paper was to give an overview of the current state of knowledge on the agricultural utilization of poultry litter, and options available to integrate litter into economically and environmentally sound management systems.

B. Manure Production And Composition

Integrated poultry production in the United States is concentrated in the midsouth region. Arkansas, Georgia, North Carolina, and Alabama account for over 40% of national cash receipts derived from the sale of poultry products; Arkansas leads all states in both quantity and cash value of poultry products. As midsouth states are crucial to national poultry production, levels of poultry production are similarly important to the economic well-being of these midsouth states - cash receipts from poultry and eggs constituted 45% and 51% of total 1989 farm income for the states of Arkansas and Alabama, respectively.

Litter associated with broiler production, manure generated from laying operations (hens and pullets), and dead birds are the three wastes of primary concern in poultry production (Edwards and Daniel, 1992). Approximately 13 million Mg of litter and manure was produced on U.S. poultry farms in

1990, most of which (45%) was generated in Arkansas, North Carolina, Georgia, and Alabama (Table 1). Broiler litter accounted for 68% of the total fecal wastes generated by the poultry industry in 1990 (Table 1). Although data on amounts of dead birds generated in poultry production are scarce, a 4% mortality rate, over a production cycle, is considered normal for most poultry operations (Edwards and Daniel, 1992). Using this value, the data in Table 1, and live weights of 0.9 kg bird⁻¹ for broilers, 0.9 for layers, 0.7 for pullets, and 5.0 for turkeys (one-half live market weights; Sims et al., 1989), approximately 270,000 Mg of dead birds required disposal on U.S. poultry farms in 1990. Commonly used, approved methods of dead bird disposal include burial pits (open bottom), incineration, and rendering. Recently, however, co-composting dead birds with poultry litter (Cummins et al., 1992), an acceptable and desirable disposal method that produces a material amenable to land application, has become popular.

Land application offers the best solution to management of the enormous amounts of manures generated on U.S. poultry farms each year. Depending on the composition of individual poultry manures, these materials can enhance crop production via their capacity to supply nutrients and increase soil quality. Broiler litter is a mixture of manure, bedding material, wasted feed, feathers, and ash (soil picked up during recovery). Bedding materials are used to absorb liquid fractions of excreta, and depending on locality, materials typically utilized for bedding include wood chips, sawdust, wheat straw, peanut hulls, and rice hulls. Owing to its relatively low moisture and high macronutrient content (Table 2), broiler litter is generally considered to be the most valuable animal manure for fertilizer purposes (Wilkinson, 1979). Broiler litter also contains significant amounts of secondary plant nutrients and micronutrients (Table 2). Chicken manure without bedding typically has a N content similar to broiler litter, but higher concentrations of water, P, Ca, Mg, and Zn (Table 2). It also has a higher proportion of N as ammoniacal-N (Table 2), which is subject to loss via ammonia volatilization. Turkey manure typically contains amounts of N and P similar to chicken manure, but a lesser concentration of K (Sims et al., 1989). Dead-bird-

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Table 1. Number of birds and manure generated (dry basis) on U.S. farms in 1990, ranked according to total amounts of manure generated.

State	Broilers		Layers ^a		Turkeys		Totals	
	Number ^b Produced	Manure ^c Gener.	Number ^b Produced	Manure ^d Gener.	Number ^b Produced	Manure ^e Gener.	Number Produced	Manure Gener.
	Millions	1000 Mg	Millions	1000 Mg	Millions	1000 Mg	Millions	1000 Mg
Arkansas	951	1427	15.3	52.8	22.0	239.8	989	1719
North Carolina	540	810	2.5	53.4	58.0	632.2	611	1496
Georgia	855	1282	18.0	55.6	2.0	21.9	875	1359
Alabama	847	1270	9.5	34.1	f	f	856	1304
California	231	347	29.0	136.9	32.0	348.8	292	832
Mississippi	413	620	6.1	24.4	f	f	419	644
Virginia	297	445	3.4	12.1	17.0	185.3	317	643
Minnesota	41	62	10.2	41.7	46.3	504.7	98	608
Texas	338	507	14.0	50.9	f	f	352	558
Maryland	265	398	3.3	8.6	0.1	1.2	269	408
Missouri	88	132	6.6	26.0	18.0	196.2	113	354
Delaware	232	348	0.6	1.5	f	f	32	349
Pennsylvania	116	173	18.7	54.3	8.4	91.9	143	320
Oklahoma	142	213	3.7	14.8	f	f	146	228
Florida	120	179	11.2	45.1	f	f	131	224
South Carolina	84	125	5.7	20.7	5.5	60.0	95	206
Ohio	21	31	17.7	74.1	4.8	51.8	43	157
Tennessee	99	149	1.1	3.6	f	f	100	152
Iowa	9	14	8.6	33.3	8.8	95.9	27	143
West Virginia	41	62	0.7	2.0	3.9	42.0	46	105
Oregon	24	36	2.6	11.8	2.3	25.1	29	72
Washington	33	50	5.0	21.5	f	f	38	71
Michigan	1	1	5.4	18.5	4.3	46.9	10	67
Nebraska	3	4	5.1	21.8	2.1	22.9	10	49
Wisconsin	14	21	3.4	18.3	f	f	17	39
New York	2	4	3.7	12.7	0.5	5.2	7	22
Kentucky	2	2	1.7	6.0	f	f	3	8
Hawaii	2	3	0.9	4.9	f	f	3	8
Other States	156	233	47.9	182.9	47.1	513.4	251	930
Total	5966	8948	272	1044	283	3085	6520	13078

^a Includes laying hens and pullets of laying age; pullets of laying age represent 56% of the total number produced.

^b Adapted from USDA (1991)

^c Broiler litter, based on 1.5 kg litter bird⁻¹ yr⁻¹ (Perkins et al., 1964).

^d Based on 7.00 kg manure bird⁻¹ yr⁻¹ for laying hens and 1.4 kg manure bird⁻¹ yr⁻¹ for pullets of laying age (Sims et al., 1989).

^e Based on 10.9 kg manure bird⁻¹ yr⁻¹ (Sims et al., 1989).

^f Included in totals for "Other States".

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compost is similar to broiler litter in its nutrient composition, except for its lower N content; N losses are inherent to the composting process (Table 2).

ing the material, such as front-end loaders. Currently, litter is removed after five growouts, which is once a year. Upon removal from poultry houses, this material may be di-

Table 2. Chemical Properties of broiler litter, chicken manure, and dead-bird compost.

Component	Broiler Litter ^a		Chicken Manure ^a		Dead-bird Compost ^a	
	Mean	Range	Mean	Range	Mean	Range
	g kg ⁻¹ material					
Water	245	220-291	657	369-770	362	217-499
Total C	376	277-414	289	224-328	232	167-270
Total N	41	17-68	46	18-72	18	13-36
NH ₄ -N	2.6	0.1-20	14	0.2-30	0.5	0.1-1.2
NO ₃ -N	0.2	0-0.7	0.4	0.03-1.5	0.1	0-0.6
P	14	8-26	21	14-34	12	7-17
K	21	13-46	21	12-32	13	8-20
Ca	14	0.8-17	39	36-60	20	11-34
Mg	3	1-4	5	2-7	4	3-7
	mg kg ⁻¹ material					
Mn	268	175-321	304	259-378	355	205-600
Fe	842	526-1000	320	80-560	3002	07-9530
Cu	56	25-127	53	38-68	392	48-746
Zn	188	105-272	354	298-388	318	163-539
As	22	11-38	29	c	c	c

^a Adapted from Edwards and Daniel (1992).

^b Adapted from Cummins et al. (1992).

^c No data.

C. Manure Management Systems

Handling systems for poultry manures encompass operations required for removal from poultry houses, pretreatment, and transport to the field. The means by which poultry manures are handled are controlled, in large part, by the moisture content of the material.

Solid Poultry Manure

Most broiler operations result in the production of solid poultry manure. Solid poultry manures (poultry litter and manure) contain 150 g dry matter kg⁻¹, which makes them amenable to solid waste handling systems (Miner and Hazen, 1977). Removal of solid poultry manure from production houses is typically accomplished with tractor-mounted box scrapers or blades and machinery capable of scoop-

rectly land applied or be temporarily stored. Manure storage prior to land application, which may occur under roofed structures (dry-stack barns) or well-secured impermeable tarpaulins, allows flexibility in timing of land application (Brodic and Carr, 1988). Flexibility in timing of spreading is important for synchronization of plant nutrient needs with nutrient release from poultry manure, which lessens the risk for environmental contamination when these materials are land-applied. Moreover, dry storage reduces the risk of environmental contamination as compared to exposed manure piles.

If stored, particularly under roofed structures, solid poultry manures may be subjected to treatments aimed at enhancing their spreading characteristics, maintaining their nutrient composition, or altering their chemical and biological properties via composting. Drying solid poultry manures at the wetter end of the spectrum, which may be accomplished via

static aeration or by mixing with drier materials, may be desirable from a weight reduction and spreading perspective. Drying is particularly desirable if solid poultry manures are to be transported long distances. However, mechanical drying (fans and/or driers) of these materials is rarely practiced. Considerable N loss owing to ammonia volatilization can occur during handling; additions of water soluble phosphate fertilizers (excluding ammonium phosphates), which react with ammonia in manures to form ammonium phosphates, have been put forward as a means to conserve N (Mitchell et al., 1990). Additions of water soluble phosphates to solid poultry manures increases the P concentration of the manure, which may be undesirable from an environmental perspective. Additions of alum may be the best method of avoiding ammonia volatilization. This would not only decrease volatilization, but decrease P runoff as well.

Runoff of dissolved P from fields receiving poultry litter can occur, even when best management practices (BMPs) are utilized. The reason for this is that poultry litter contains high concentrations of water soluble P (often in excess of $2,000 \text{ mg P kg}^{-1}$). This fraction is readily transported in runoff water during intense rainfall events.

Recent work has shown that the level of water soluble P in litter can be reduced by several orders of magnitude with the addition of flocculating materials commonly used in wastewater treatment and lake restoration. Moore and Miller (1992) showed water soluble P levels decreased from around $2,000 \text{ mg P kg}^{-1}$ to less than 1 mg P kg^{-1} litter with the addition of aluminum, calcium and iron compounds such as alum, slaked lime and ferrous chloride. These compounds not only reduce water soluble P concentrations, but also decrease suspended solids, biological oxygen demand, heavy metals, bacterial counts, virus viability and parasites.

Composting, which occurs naturally when non-sterile organic substrates are combined with water and oxygen, may be a desirable treatment for poultry manures. In the composting process, which may be applied to solid poultry manures and/or poultry mortalities, aerobic microbial decomposition gener-

ates sufficient heat energy to raise the temperature of compost mixtures to the thermophilic zone ($40\text{--}75^\circ\text{C}$), destroying pathogenic organisms and weed seed at temperatures 60°C . Composting reduces the volume and weight of original organic substrates, and the end result of successful composting is a material that is biologically stable, odor-free, and useful as a potting media and soil amendment.

Liquid Poultry Manures

Liquid poultry manures (those containing $<150 \text{ g dry matter kg}^{-1}$) are generated when manure is scraped or flushed into storage reservoirs, such as tanks, detention basins, aerobic or anaerobic lagoons, and oxidation ditches. Most of the liquid poultry manure is generated in laying hen operations. While these materials are generally amenable to hydraulic pumping, those containing between 40 and $150 \text{ g dry matter kg}^{-1}$, referred to as slurries, can present problems to pumping equipment because of their viscosity and the potential to plug orifices (Miner and Hazen, 1977). Solid-liquid separation via sedimentation or filtration may be necessary when liquid poultry manures with higher amounts of solids are to be pumped. Although storage in reservoirs often serves to enhance hydraulic properties of liquid poultry manures with regard to ease of pumping, these systems can result in considerable loss of plant nutrients. Ammonia volatilization losses from storage reservoirs range from 25 to 80% of original N contained in liquids/slurries, and P and K losses range from 5 to 50% of original P and K (Tisdale et al., 1985). Nitrogen losses are minimized when the liquids/slurries are added to the bottom of storage reservoirs instead of the surface (Loehr, 1984).

D. Land Application Of Manure

Except for small amounts of poultry manure used in animal feed, the major portion (90%, Carpenter, 1992) is applied to agricultural land. This application usually occurs no more than a few miles from where it is produced. Thus, in states with a large or growing

poultry production industry, increasing demands are being imposed on agricultural acreage to efficiently utilize the nutrients (primarily N and P) contained in the manure. In the major poultry producing states, the amounts of nutrients produced in manure exceed crop requirements. Data compiled by NASS (1989), indicates that the amount of P produced annually in poultry manure exceeds that required by the 3 major crops in several states (Fig. 1). Poultry production is often concentrated in regions with small farms with very limited acreages for land disposal. While poultry production provides economic incentives for these small farmers, problems cre-

tion. Assuming poultry litter contains a respective N and P contents of 3.4 and 1.7% (dry-weight basis), a farmer would have to add 5 times as much poultry litter as 17-17-17 fertilizer to achieve the same N and P application rate.

Transport of solid poultry manure to the field, depending on the distance, is typically done with spreader or large-bodied trucks. Liquid poultry manures containing between 40 and 150 g dry matter kg^{-1} (slurries), may be pumped from storage reservoirs into tank-bearing vehicles for transport to the field, which requires agitation (Miner and Hazen, 1977). Liquid poultry manures having 40 g

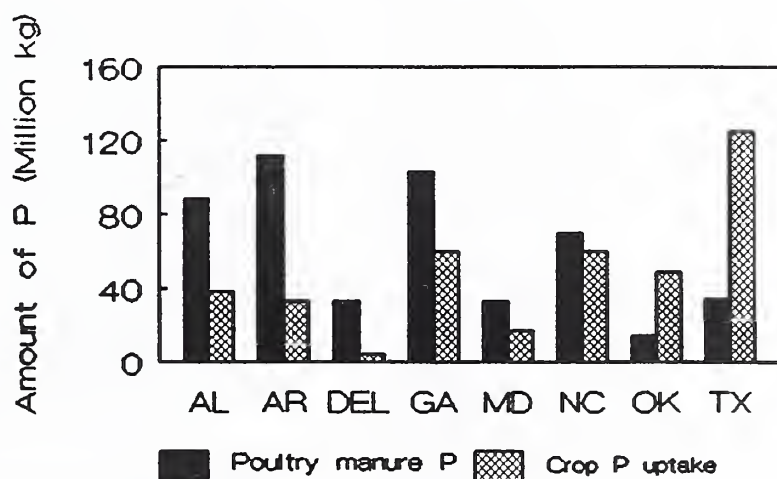


Figure 1. Amount of P produced in poultry manure and taken up by the three major crops in several poultry producing states for 1988 (data adapted from NASS, 1989)

ated by utilization of manure produced by these enterprises may have major environmental consequences.

Transportation

Generally, transportation of poultry litter is restricted to less than 10-20 km. Due to the concentrated nature of manure from poultry layers, which usually has no bedding material, this form of manure may be economically transported greater distances than other manures. Obviously, being able to transport the manure greater distances from the source of production increases the acreage for applica-

dry matter kg^{-1} may be handled in the same manner as slurries, or be pumped directly from storage reservoirs into pipeline systems, which deliver the material to irrigation equipment at the site of application.

Overcoming the economic restrictions to a farmer, allowing movement of poultry litter to a greater acreage where the manure could supplement or even replace mineral fertilizer requirements, is one of the major obstacles facing the more efficient utilization of poultry manure. The recent trend of several neighboring farmers to form cooperatives that can more cost-effectively compost and compact manure, should be encouraged by cost-shar-

ing programs. By composting and compacting, the bulk density of the manure is increased, which reduces the cost of transportation.

In addition, education and extension programs should highlight the nutritive and mulching value of poultry manure for non-poultry-producing farmers. This should increase the demand for this nutrient resource.

Spreading Equipment

The type of spreading equipment used depends on the practiced methods of storing and handling poultry manure. Traditionally, poultry manure is broadcast directly from the house, using a variety of spreaders with a shredder attachment. Manure stored in deep pits is removed by scraping and applied similarly with a spreader. In a few cases, manure stored in shallow pits is removed by flushing and, after large solids have been removed by sedimentation and/or filtration, is applied with an irrigation system. Spreading equipment can vary with contractor and has thus seen little standardization. In many locations where the poultry industry has recently expanded, existing farm equipment is used to apply the manure. There has been less progress in improving spreading equipment for solid manure than that for liquid manure.

Because of concerns with surface water quality in areas of intensive poultry production, there is a need for equipment for subsurface application of the bulky manure, particularly in grass or fescue production systems. It is likely that these methods will be labor and energy intensive and thus, be of limited applicability to many farmers. Equipment development should also involve better control of the application rate and provide even distribution of manure.

Land Base Available

In most cases, the land base available for application of manure is limited. This limitation mainly arises from restrictions imposed by the economics of manure transportation as discussed earlier. Consequently, poultry ma-

nure is usually applied in the immediate vicinity of the production site. Thus, the dominant geology, soils, and topography of the local area often cannot be considered prior to application. This inflexibility may result in the application of manure to areas with elevated soil N and P contents from previous applications or with high runoff or leaching potentials. Consequently, recommended manure application rates should be flexible and account for differing geology, soil, and topography of potential application sites.

Proliferation of the poultry industry has been economically driven. Numerous farmers with limited resources have turned to poultry production as a ready source of income, with limited cash outlay. In many areas of the southern U.S., intensive poultry production has developed on agricultural land unable to maintain high crop yields, due to such factors as erratic weather, sloping topography, or soils that are shallow, coarse textured, or highly permeable. Therefore, local need for N and P in such regions would be lower than in areas of intensive crop or forage production.

Manure applications may be based on soil test P requirements rather than on crop N requirements. Currently, most manure application rates are based primarily on the management of N to minimize nitrate losses by leaching. In most cases, this has led to an increase in soil P levels in excess of crop requirements due to the generally lower ratio of N:P added in poultry manure than in crops. For example, poultry manure has an average N:P ratio of 3 (Table 2), while the N:P requirement of major grain and hay crops is 8 (Fig. 2 from Fertilizer Handbook, 1982). Because of the relatively greater accumulation of P than N in soil receiving continual application of poultry manure for several years, the soil test P level in these soils far exceeds that required for 100% sufficiency of many crops (Sharpley et al., 1991b; Sims, 1992; Wood, 1992).

A P driven approach may mitigate the excessive build-up of soil P and at the same time lower the risk for nitrate leaching to groundwater. However, a soil test P based strategy would eliminate much of the land area with a history of continual manure applications, as many years are required to lower soil P levels,

Crop	Yield Mg ha ⁻¹
Alfalfa	18
Coastal Bermuda	22
Corn	12
Potatoes	25
Soybean	4
Wheat	3

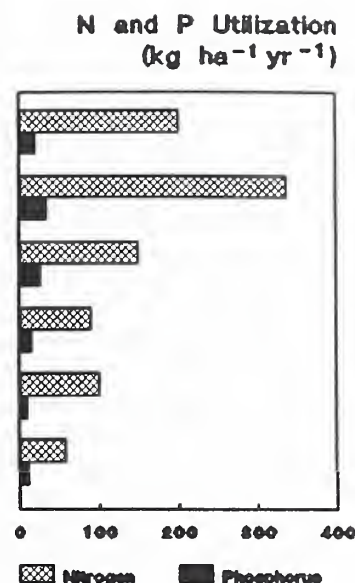


Figure 2. Approximate annual N and P utilization by several crops (data adapted from Fertilizer Handbook, 1982)

once they reach excessive levels (Kamprath, 1967; Wood, 1992). In addition, farmers relying on poultry manure to supply most of their crop N requirements will have to purchase commercial fertilizer N, instead of using their own manure N. Using a soil test P based strategy may resolve potential environmental issues, but places unacceptable economic burdens on farmers.

Finally, lower manure application rates and a reduction in the land base available for application will further exacerbate the problem of local land limitations. Hydrology of the available land base will also be important in determining if manure application rates should be based on N or P. If the potential for leaching of soluble chemicals from an application site exists, one could argue that N should be a priority management consideration. Conversely, if runoff and erosion potential far exceed leaching potential, then P would be the main element governing application rates.

As the poultry industry continues to grow in areas of intensive production where the land base suitable for agronomically and environmentally sustainable manure applications continues to decline, manure will by necessity, be moved outside intense poultry producing areas where it will be a valuable N, P, and organic matter resource. Research in

Alabama, Arkansas and Oklahoma is evaluating appropriate application rates and cultural practices for poultry manure as a nutrient source for field crops (corn, cotton, rice, sorghum and wheat) and bermudagrass (coastal and midland). However, cost of transporting manure from areas of intensive production to regions where the above crops are grown extensively remains as a major obstacle.

Tillage Effects

Application of poultry manure before or during tillage will reduce surface soil accumulation of added N and P and increase their distribution in the root zone. If a ground cover can be maintained during times of the year when runoff producing rainfall is common, environmental risks will be reduced while crop utilization of N and P will be increased. Preliminary research in Arkansas and Oklahoma using simulated rainfall on soil receiving poultry manure indicated that soil incorporation of manure with tillage reduced N and P loss in surface and subsurface runoff compared to broadcast applications. This effect was attributed to a dilution of manure N and P in the depth of tilled soil.

However, when applied with tillage, the time frame for manure application will be re-

stricted to the time frame needed for tillage operations. In addition, incorporation of manure increases labor inputs in the short time available for seedbed preparation, and can sometimes delay sowing and increase weed problems. The use of manure on grassland without tillage can be reasonably efficient, especially in areas with a humid climate (Tveitnes, 1979). This is probably because grass species can utilize N and P from the manure throughout the whole growing season.

Soil and Manure Testing

There are many variables associated with poultry management systems that can affect manure quality at the time of application. These include the type and amount of bedding material used, accumulation time, feed, amount and quality of water used to flush the house, location in a storage pit at which the manure is removed, and length of storage before land application. The variability in these management factors can result in a wide range in the nutrient composition of the manure applied (Edwards and Daniel, 1992).

As a result, farm advisors and extension agents in several states are recommending that the N and P composition of both manure and soil are determined by soil test laboratories before land application of manure. There is also a tendency among farmers to underestimate the nutritive value of manure. Thus, manure analyses are a constructive educational tool showing farmers that manure represents a valuable source of N and P.

In those states where manure analyses are conducted, total N, ammonium N ($\text{NH}_4\text{-N}$) and moisture content are generally determined. With the use of more sophisticated analytical equipment allowing multi-element analysis in soil test laboratories, total P, K, and other nutrients can also be determined and reported to the farmer upon request. As most of the N and P in poultry manure is in organic forms (90 and 60%, respectively, Edwards and Daniel, 1992; Wood and Hall, 1991), much of the N and P is not immediately available to plants. Thus, for maximum crop production, N and P application based on

total contents may need to be greater for manure than inorganic sources.

Manure application based on total nutrient contents are adjusted to account for nutrient availability in soil. Nitrogen availability is related to mineralization of organic N (usually 50 to 60% of the organic N fraction) and recovery of added $\text{NH}_4\text{-N}$. This availability may be adjusted further to account for the effect of storage time on N mineralization and volatilization and of soil type on $\text{NH}_4\text{-N}$ fixation. It is generally assumed that 75 to 80% of added total P and all the K is plant available. A cautionary note to basing application rates on manure analyses must be sounded, because of the wide variability in nutrient contents that can be obtained. For example, variabilities associated with sampling the manure alone can be 10 to 15 g N kg manure⁻¹ (25 to 35 lbs N ton⁻¹). This could amount to a 25% over or under estimation of N content (Table 2). Thus manure analysis should be used as guidelines only.

Current soil test methods represent, for the most part, plant available inorganic N and P levels in soil. Because of the high organic N and P content of manure, soil test recommendations must give credit to the mineralization of organic nutrients during the growing season. In addition, poultry manure can provide plant available N and P for several years after application. Thus, soil tests must also give credit to the residual effects of poultry manure, possibly resulting in a reduction in application rates in years following initial applications. In many instances it is difficult to develop accurate credit for the variable soil, climate and cropping conditions encountered.

Cost Effective BMPs

The utilization of poultry manure can be a valuable natural resource in cost-effective BMPs. In many areas of intensive poultry production, manure applied on hilly land has increased vegetative cover, thereby reducing runoff and erosion potential. These unproductive soils would not normally receive mineral fertilizer, thus, the careful use of poultry manure can reduce environmental degradation.

Based on the above discussion, the use of poultry manure in BMPs must consider crop type, timing of application, land base available and previous applications. Crop type and yield will affect the amount of N and P removed from the production system, if the crop is harvested (Fig. 2). Obviously, the accumulation of manure N and P within an agricultural system will be reduced if it is removed from the farm in the harvested crop.

E. Alternate Uses Of Poultry Litter

Poultry litter, when mixed with feed grains, has been found to be a successful feed for cattle. Approximately 4.2 percent of the poultry litter produced in the United States is fed to cattle (Carpenter, 1992). In some states, high quality poultry litter (20% crude protein and less than 10% ash) can be worth as much as \$99 per metric ton as feed, whereas the same litter may only be worth \$33 per metric ton as fertilizer (Payne and Donald, 1992).

Although disease problems have not been reported from feeding manures to animals under acceptable conditions, copper toxicity has been reported to be a problem in sheep (Fontenot et al., 1971). The litter contained 195 mg Cu kg⁻¹ due to feeding chicks high levels of copper sulfate. Currently, most poultry producers feed an excess of copper sulfate. Although this results in an increase in weight gain, the gains are not due to a change in diet *per se*, but rather to a change in litter composition (Johnson et al., 1985). There are two possible explanations for this phenomenon; (1) high copper levels in the litter reduced populations of pathogenic microorganisms, and (2) non-biologically mediated reactions, such as ammonia volatilization, are affected.

It is important to remove any foreign materials from the litter when it will be used for feed. These materials include wire, plastic and glass. It is also important to maintain a low ash content. When large quantities of soil are removed with the litter, the ash content increases dramatically. Litter with ash contents exceeding 28% should not be fed to cattle.

Composted poultry litter is also sold to nurseries and garden stores as an organic amendment. However, at present the amounts sold in this manner represent much less than one percent of the total litter produced. Poultry litter may also power electricity production. A power station using poultry litter became operational in Suffolk, England, in 1992. The power plant cost approximately \$35 million and will use 10,000 Mg of litter per year from the area's poultry farms.

F. Agronomic And Environmental Effects

Soil Properties

In addition to benefits that poultry litter and manure provide to crop production in the form of nutrients, these carbon (C) bearing materials can build soil organic matter reserves, which benefits crop production via increases in soil water-holding capacity, water infiltration rates, cation exchange capacity, and structural stability. Weil and Kroontje (1979) found that high rates of poultry manure when incorporated into the soil resulted in decreases in bulk density, and increases in water holding capacity and water stable aggregates. Kingery et al. (1993) showed that litter applications resulted in increased organic C and total N to depths of 15 and 30 cm, respectively. Litter improves the water holding capacity of soils, as well as infiltration. Soil tilth is also improved by increasing organic matter contents by applying litter.

Metals, such as arsenic (As), copper (Cu) and zinc (Zn), are often fed to poultry. This results in average concentrations in the litter of 22, 56, and 188 mg metal kg⁻¹, respectively (Table 2). Kingery et al. (1993) found elevated levels of K, Ca, Mg, Cu and Zn in soils heavily fertilized with poultry litter. Elevated levels of heavy metals in the soil will result in increased uptake by plants, which will be consumed by animals or man. However, normally concentrations do not reach toxic levels.

Soil Fertility

Poultry litter is generally considered the most valuable of animal manures for use as a fertilizer, due mainly to its low water content. As mentioned earlier, poultry litter contains large amounts of N, P, K, as well as secondary, and trace elements. Under certain conditions, various salts can build up from excessive poultry litter applications. Soil salinity attributed to poultry litter applications has occasionally been shown to reduce germination and growth of corn (Shortall and Liebhardt, 1975; Weil et al., 1979). However, it should be pointed out that poultry litter has long been recognized as an ameliorant to salt affected soils. Research by Hileman (1973) showed that poultry litter promotes growth on brine-contaminated soils in South Arkansas.

Stephenson et al. (1990) found that the average fertilizer equivalent of litter was 3-3-2 (%N, P₂O₅, K₂O, respectively) when determined on an "as spread" basis. Litter also contains substantial quantities of B, Ca, Cu, Fe, Mg, Mn, S and Zn.

Nutrient imbalances in forages due to excessive litter applications have been observed. Grass tetany in ruminants, which is related to the K/(Ca + Mg) balance in forages, appears to be more likely on soils which received excessive rates of poultry litter in the past (Wilkinson et al., 1971), possibly due to high K levels in litter. Therefore, litter application rates should be limited to 9 Mg ha⁻¹ or less for use on fescue.

Poultry litter has also been found to be a valuable amendment for rice soils which have been leveled by grading. Miller et al. (1991) showed rice yields increased as much as 286% with chicken litter additions. Although they did see some yield responses when inorganic N, P, K, S, and Zn fertilizers were added at the same rate, these responses did not match those resulting from poultry litter.

Water Quality

Dense confinement and spatially concentrated manure production are inherent characteristics of efficient, integrated poultry

production systems. The customary method of poultry manure utilization is land application without incorporation, a practice which also increases the fertility of receiving areas. However, the same nutrients which make poultry manure a good fertilizer can, under some circumstances, be detrimental to the quality of ground water and downstream surface water. The potential for water quality degradation from nutrients responsible for eutrophication (N and P), oxygen-demanding materials (organic carbon), and selected metals is of particular interest in areas such as Northwest Arkansas where shallow, cherty soils and karstic geology greatly increase the interaction between surface and ground water.

One of the primary health concerns with excessive poultry litter applications is nitrate leaching into the groundwater. The EPA limits nitrate concentrations in drinking water to 10 mg NO₃-N L⁻¹. Liebhardt et al. (1979) found that excessive applications of litter to corn resulted in nitrate leaching through the profile and elevated nitrate levels in groundwater. Ritter and Chirnside (1982) indicated that 32% of the water wells in Sussex County, Delaware had high nitrate levels (10 mg N L⁻¹) due to improper poultry litter applications. Kingery et al. (1993) found that high loading rates of poultry litter resulted in buildup of nitrate in the soil to 3 meters depth or to bedrock (Fig. 3).

From a surface water viewpoint, P is the element of primary concern, since it is generally considered to be the limiting nutrient for eutrophication. Excessive applications of poultry litter to soils result in a buildup of P near the soil surface. Kingery et al. (1993) observed soil test P levels as high as 225 mg P/kg soil in the soils in Sand Mountain area of Alabama (Fig. 3).

In a similar study of continual long-term poultry litter application to 12 Oklahoma soils, Sharpley et al. (1993) found that P accumulated in the surface meter of treated soil, to a greater extent than N (Figure 4.). This reflects the differential mobility, sorption, and plant uptake of N and P in soil.

Using kinetic and enrichment ratio approaches, the movement of P in soluble and

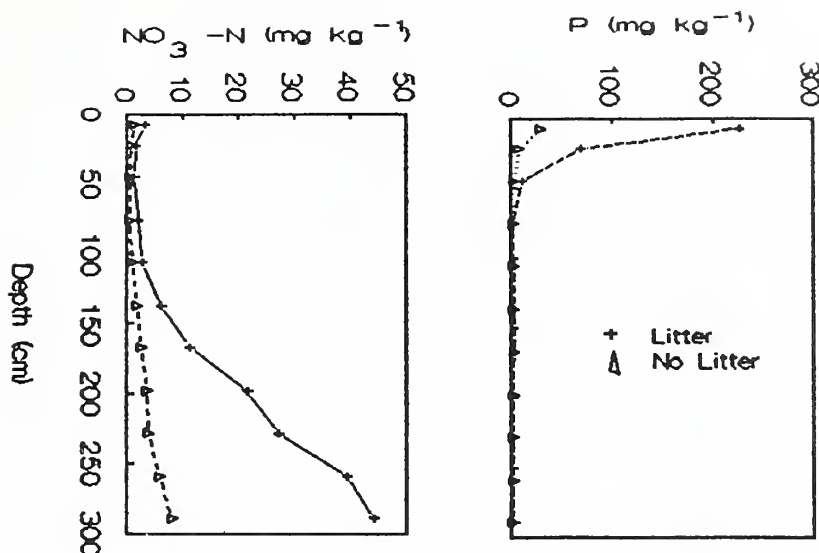


Figure 3. Average soil $\text{NO}_3\text{-N}$ and extractable P concentrations for 12 pasture pairs in the Sand Mountain Region of Alabama that have received long term application of broiler litter or no litter.

sediment-bound (particulate) forms as a function of agricultural management can be predicted (Sharpley and Smith, 1993). Using these approaches, the P concentration of a 2.5 cm runoff event of $10 \text{ kg ha}^{-1} \text{ yr}^{-1}$ soil loss was predicted for grasslands in Oklahoma. Predicted P concentrations of runoff from three soils treated with poultry litter were much greater than from untreated soils (Figure 4). Under grass, erosion is minimal and, thus, most of the P will be transported in a bioavailable form (80%, i.e., soluble and NaOH extractable particulate P available for algal uptake). These concentrations are two orders of magnitude greater than values associated with eutrophication (0.01 and 0.02 mg P L^{-1} soluble and total P, respectively, Sawyer, 1947; Vollenweider and Kerekes, 1980). The potential increase in P transport in runoff highlights the need for careful management surface soil accumulations of P as a result of poultry litter applications on soil susceptible to runoff and erosion.

Recent research in Tennessee on well water protection on poultry farms indicated that 43% of the wells sampled contained fecal coliform bacteria and 8% of the wells exceeded $10 \text{ ppm NO}_3\text{-N}$ (Goan and Burcham, 1992). They found that well location was an important factor with regard to contamination, and indicated that wells should be at least

15.2 meters from chicken houses and 30.4 meters from stacked broiler litter.

Poultry wastes are known to contain many potential pathogens. Alexander et al. (1968) tested 44 poultry litter samples for the presence of pathogens. They found 10 different species of *Clostridium*, three species of *Salmonella*, two species of *Corynebacterium*, one species of yeast and one species of *Mycobacterium* (which is occasionally responsible for tuberculosis) in various litter samples. All of the litter samples contained *Enterobacteriaceae* (other than *Salmonella*), *Bacillus* spp., *Staphylococcus* spp., and *Streptococcus* spp. In Arkansas, the nation's leading poultry producing state, 90% of the surface water bodies (statewide) sampled by the Arkansas Department of Pollution Control and Ecology contained fecal coliform counts in excess of the primary contact standards. However, fecal coliform counts prior to the rise in poultry in this state are not available. Therefore, it is unknown whether these levels are indigenous or, in fact, due to runoff from animal manures.

Viruses have also been reported in poultry litter and may represent a greater problem than bacteria. These include viruses responsible for New Castle disease and Chlamydia (Biester and Schwarte, 1959). At present, very

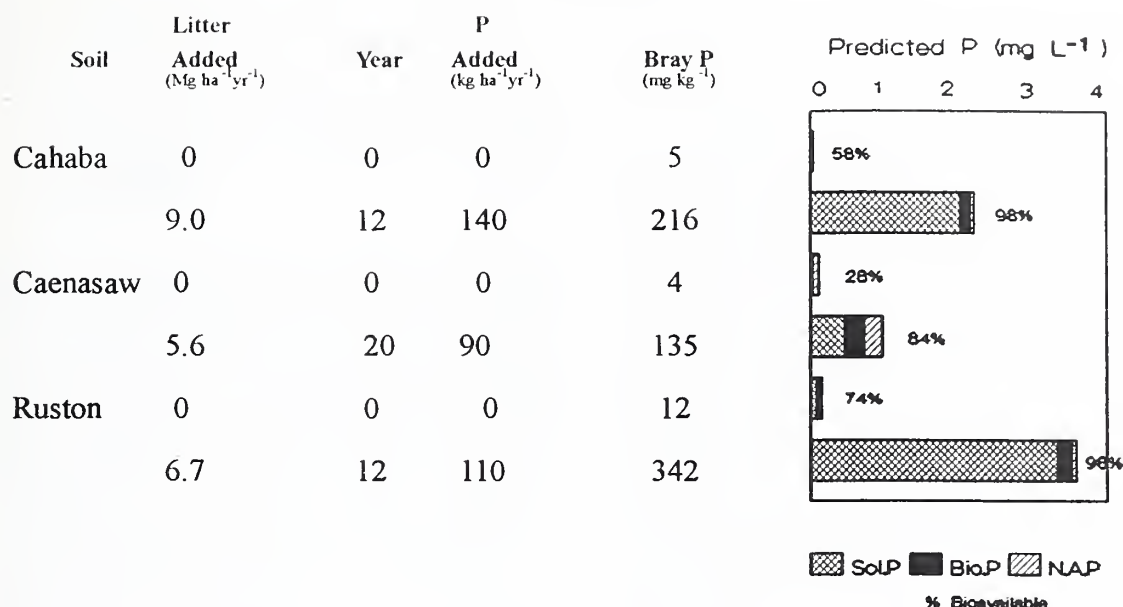


Figure 4. Predicted soluble, bioavailable particulate and non available P in runoff grass receiving poultry litter.

little information on virus runoff from fields receiving poultry litter is available.

Air Quality

Odor problems are the number one complaint against animal growers received by state and federal environmental regulatory agencies (Williams, 1992). Much of the odor is due to high levels of ammonia. Volatilization of ammonia results in decreased poultry productivity due to an increase in the incidence of ascites and other respiratory related maladies, such as Newcastle Disease. Ammonia volatilization also results in tremendous N losses that could otherwise be used for fertilization of pasture or cropland. Wolf et al. (1988) found that 37% of the total N applied on the surface of a pasture was lost via volatilization after only 11 days. With the inclusion of in-house losses, this figure would increase to well over 50% of the total N. Another reason ammonia volatilization is detrimental is the negative impact it has on the environment with respect to acid rain.

Atmospheric ammonia concentrations as low as 5 $\mu\text{L L}^{-1}$ can be detected by humans; with some susceptible to eye irritation at levels as low as 6 $\mu\text{L L}^{-1}$. Currently, OSHA has not set exposure levels for U.S. poultry work-

ers, however, in Europe the COSHH (Control of Substances Hazardous to Health) has determined exposure limits to humans at 25 $\mu\text{L L}^{-1}$ for an eight hour exposure and 35 $\mu\text{L L}^{-1}$ for a 10 minute exposure (Williams, 1992). Since ammonia volatilization is a function of the NH_3/NH_4 equilibrium, which is pH dependent, research should be conducted on cost effective litter amendments which lower the pH beyond the point at which volatilization can occur. Hopefully, these treatments will pay for themselves by increasing weight gains of the birds and increasing the quantity of N available in manure for land application.

Crop Production

Poultry litter and manure have increased yields in many different crops, such as bermudagrass, corn, fescue, orchardgrass, rice and wheat (Edwards and Daniel, 1992; Miller et al., 1991; Wood, 1992). Most of the yield increases have been reported to be due to the N content of the litter, however, the response in rice on graded soils which occurs in Arkansas cannot be duplicated with inorganic N, P, K, S, and/or Zn (Miller et al., 1991).

G. Issues and Options

Education and Technology Transfer

Technology transfer in production agriculture has become a fairly familiar process. For example, if a new herbicide is developed it will undergo field testing by industry and universities, and if proven successful, information will be made available through a variety of mechanisms, including field days, extension brochures, industry field personnel, published journals and other outlets. A tried and proven infrastructure exists for getting the proper information to the potential user in an efficient and timely manner. Equally important, everyone is aware of the target audience, in this case the grower/farmer are the primary audience.

For several reasons, transfer of technology relating to nonpoint pollution, especially poultry waste management, differs markedly from production agriculture. At least initially, the state and federal agencies are involved in water quality and grower/farmer is not the target audience for new information. Within each state, a state agency is often designated as the lead agency concerning nonpoint source pollution. This is complicated by some agencies having jurisdiction for surface and not for ground water. In such cases, a lead agency is still identified, but one agency may take surface waters and the other ground water. The issue is further complicated by federal agencies such as the USDA-SCS which implement practices that conserve soil and water. This agency should have a major role in the decision making process because it has responsibility to design and implement the selected BMPs. When dealing with poultry waste, the poultry processing and retailing industry is a major player because its management program is dynamic and can have significant impact on the amount and quality of litter produced. For example, current estimates for the amount of broiler litter produced is approximately 1.5 Kg/bird. Future projections are that this number will be reduced significantly (2%) because the industry is moving to a clean out schedule of every two

years instead of annually and with only half of the litter taken.

Clearly, this is uncharted water when it comes to technology transfer and for that matter the conduct of research. Applied research implemented as a BMP can not be done in a vacuum. For proper planning and conduction of research, the researcher must have input and an ongoing dialogue with every player, including industry personnel, state and federal agencies, and ultimately the grower. As information is generated, these same players must be appraised of developments. The initial target audience for this information is the professionals working in the water quality area, especially those agency professionals deciding which practices will be identified as a BMP. The first step in this process is to establish scientific credibility by journal publication and presentations. Concomitant with the first step, this same information needs to be repackaged and transferred to state and federal agency personnel working in the water quality area. Information transfer to this group may take several avenues, including workshops, brochures, seminars, etc. A parallel process needs to occur with representatives of the poultry industry and selected growers. This is a necessary, time consuming, and dynamic process of identifying a series of BMP.

Ultimately, the information must be disseminated to the end user or grower and when the process reaches this point, everyone is on familiar ground. The USDA Cooperative Extension Service and the USDA-SCS, provide the critical link between the farmers and public agencies. The Extension service has primary responsibility of information dissemination to the farmers. The USDA-SCS is the technical arm at the county level that incorporates the BMPs into the farm plan.

Government Regulations and Conflicts

Conflicts within BMPs between SCS residue management guidelines and recommended manure application, may exist. In compliance with residue conservation programs, farmers may be required to maintain a 30% residue ground cover. Under this BMP,

subsurface application or knifing of manure, which may be recommended in order to minimize surface water degradation or odor problems, may not be acceptable if it reduces residue cover. Thus, BMPs' should be flexible enough to enable modified residue and manure management plans to be compatible.

Best Management Practices

The concept of BMPs was introduced in Public Law 92-500 which outlined several rigorous requirements for a practice to qualify as a BMP. The practice must relate directly to water quality and it must be cost effective. This difficult and ambiguous requirement forces the establishment of a dollar value on water quality. For example, the cost effectiveness of a practice that controls animal manure runoff near a trout stream is easier to evaluate than the benefit of implementing the same practice near a less sensitive water resource. Until better methods are developed, the process will continue to be a delicate balance between the value of the resource and cost of the practice and most likely will require consideration on a case by case basis. Acceptability and economic returns to the grower is another requirement, otherwise volunteer adoption will be low. Generally, practices that increase net income are compatible with water quality; however, accomplishing this requires a higher level of management by the grower as well as the USDA-SCS technician developing and implementing the farm plan.

Adverse impacts resulting from land application of poultry manure may be prevented by implementation of effective BMPs. Examples of BMPs include use of buffer zones between treated areas and waterways, applying the litter when there is a low likelihood of rainfall in the near future, and light incorporation where soil and topography permit. BMP implementation for litter disposal in Arkansas is voluntary or in association with cost-sharing programs.

Most specialists will agree that implementation of a combination of practices adopted as "best" will, in fact, have a positive effect on quality of runoff from areas treated with poultry litter. It is much more difficult,

however, to identify the effectiveness of individual practices because supporting data are quite limited. A lack of data on BMP effectiveness makes it difficult to quantify the water quality effects of BMP implementation and may therefore cast doubt on the appropriateness of policies and/or recommendations developed by decision-making organizations.

Best management practices are available now that will protect and maintain water quality, others are in the process of being developed and field tested. Some of these practices were initially used for erosion control and have been around for some time, while others are new and were designed specifically for protecting water quality. Generally there are three categories for classifying BMPs that address water quality problems associated with animal wastes (Logan, 1990a). These were structure control, source control and land management.

Structure and Source Control

Practices that fall into this category are those that limit pollutant transport through water management. Examples include terraces, grass waterways, buffer strips, manure storage facilities, dead bird composters, sediment catch basins, and so forth. These practices have a proven record of effectiveness. For example, buffer zones installed below cattle feedlots have proven effective in reducing transport of both N and P. Doyle et al. (1977) found that a 4 m fescue buffer zone reduced concentrations of dissolved P by 62% and nitrate by 68%. Young et al. (1980) observed total N and P reductions of 88% and 87%, respectively, for a 30 m orchardgrass buffer zone. A sorghum-sudangrass mixture buffer zone performed similarly, with 81% and 84% reductions in total N and P, respectively. Generally, these practices involve a capital cost and are easy to install and maintain. Cost-sharing is usually provided as an incentive for adoption.

These practices are very effective, easy to manage, and include practices that focus on controlling the problem at the source rather than after entry into the aquatic system. Exam-

ple practices include limiting manure application rates, application of manure only on certain slopes and time of year. Westerman et al. (1983) demonstrated a direct relationship between the quality of runoff water and application rate of poultry waste. Rainfall intensity and soil type were also shown to significantly affect total solids transport. McLeod and Hegg (1984) investigated impacts of different fertilizers (organic and commercial) on runoff quality and reported "minimal" nutrient losses (4% total Kjeldahl N, 2.5% total P). The highest nutrient losses occurred on plots treated with commercial ammonium-nitrate. Giddens and Barnett (1980), showed that high application rates of poultry litter drastically reduced the volume of runoff water and soil erosion, while increasing the coliform bacteria in the runoff.

Timing manure applications to coincide with maximum crop uptake and minimum runoff potential will enhance utilization of manure. In Arkansas, computer simulations have shown that windows for optimal timing of application of manure exist (Edwards and Daniel, 1992). Although this simulation assumed that N and P were of equal concern, it indicates that careful timing of manure applications should be part of a BMP. However, demands on farmer's daily schedules and use of independent contractors often limit the practicality of precise timing of manure applications. As a result, application timing is possibly the greatest obstacle to better manure management, with many BMPs needing to be done at the busiest times of the year for farmers.

Moving poultry litter to areas where soil N and P levels are low would not only improve crop production, but would decrease the likelihood of environmental problems associated with excess litter. In Arkansas, the poultry industry is concentrated in the northwest section of the state in the Ozark Highlands. However, most of the row crop agriculture is located in the eastern portion of the state in the Mississippi Delta. Transporting the litter from the Ozarks to the Delta would appear to be one solution to the current problem. However, the cost of transportation would prohibit this practice, unless the government or the industry provides subsidies for such a program.

Land Management

These practices manipulate the soil system to minimize pollutant loss to surface or ground water. Practices include timing and placement of manure, application method (broadcast versus incorporation), nutrient management, and irrigation scheduling of liquid manure to limit ground water contamination. Runoff losses of soluble P are affected by land application of commercial fertilizer and animal manure and the amount lost in the runoff is directly related to how the materials are managed (Baker and Laflen, 1982; Logan, 1991). These losses are often linearly related to application rate with greatest losses of P occurring when the fertilizer or manure is broadcast and not incorporated (Mueller et al., 1984; Baker and Laflen, 1982). Various investigators have shown that the level of soil test P also influences the concentration and eventual loss of soluble P in runoff. In fact, a highly significant linear relationship has been demonstrated between the level of soil test P in the surface soil and soluble P concentration of surface runoff (Hanway and Laflen, 1974; Romkens and Nelson, 1974; Sharpley et al., 1978, and 1981; Oloya and Logan, 1980).

Program Implementation, Agency Interactions, Costs And Benefits

Ensuring compatibility between poultry waste and water quality requires a continued and long-term commitment from industry, citizens and public agencies. To assure a favorable cost benefit ratio, priority watersheds should be selected to focus sparse implementation funds and expertise. Such watersheds can be selected on regional, state or local basis. The criteria for selection should be based on severity of the problem and the benefit to water quality. The complexity of the issue means that management programs will not be easy to establish or maintain. It is also clear that the concept of zero discharge is not workable. In many cases, we may only be able to maintain lakes and streams at their present state and not improve their water quality but simply keep them from deteriorating further. The inherent fertility of other aquatic systems

may have progressed to such an extent that no improvement is guaranteed regardless of funds expended.

Although BMPs are being developed for dealing with poultry waste, institutional mechanisms for implementing this technology need improvement. For example, cost-sharing programs have traditionally focused on support production practices, and only recently has the shift been made to supporting practices that protect water quality. Changing the tax laws is another approach that might accelerate implementation of environmental technology. Voluntary adoption and dissemination of new technologies that protect water quality will require agricultural producers to be convinced that the adoption of these practices is in their best interest. Dissemination of information on the relative profitability of management options and the importance of agriculture's role in water quality protection will be essential. The successful design of environmentally sound management practices must be coordinated with the institutional mechanism developed to promote adoption. Successful programs will emphasize management, control of the problem at the source by implementation of BMPs, and, perhaps most of all, informal planning sessions between the USDA-SCS field technician and the grower to produce a field-by-field farm plan that protects water quality.

Sociological Benefits

As the human population continues to grow, ever increasing strains are placed on natural resources. Recently, there has been an increased awareness of the pressures being placed on the environment from human activities. Sustainable agriculture appears to be one important means by which we can minimize the impact of food production on the environment. Utilization of animal manures for fertilization of crops will decrease the amount of inorganic fertilizers needed. This will conserve fossil fuels which are needed to produce these products and should also improve the fertility status of soils by providing a well balanced fertilizer and increasing soil organic matter. Also, if more nutrients in manure are recycled through agricultural crops, less of

these nutrients escape to the environment and result in environmental degradation.

H. Needs

Historically, strategies for land application of animal manures have been based on meeting the N needs of the crop being produced. Perhaps some aspect for this approach can be justified on the basis of ground water protection but little can be gleaned on the basis of surface water protection. Therefore, the question as to whether poultry litter applications should be based on P loading, rather than N loading, has arisen. Research aimed at determining the best approach is needed.

Soil test P levels clearly influence soluble P concentrations in the runoff. Thus, fundamental and applied research is needed regarding the critical level above which additional P should only be applied with limitations. Information is needed as to how this critical level will vary with soil types, slope, crops and management.

Use of critical soil test P levels should be applied at a watershed level rather than at the farm level because P losses are rarely uniformly distributed within a watershed (i.e., critical P contributing areas exist due to land use and natural processes). In addition, the watershed is the logical unit for correlating land use with the impacted water body. To aid in developing a cause and effect relationship, runoff models need to be refined to better account for P losses from various land use scenarios.

The traditional methods of analysis for P in the soil should be reviewed in light of the move to sustainable agriculture and conservation tillage. Under these systems and where land application of manure is practiced, the pool of soil P appears to be changing (Pierzynski et al., 1991; Sharpley et al., 1991b) and this may not be reflected by the traditional soil test. In some cases, soil test results may suggest the addition of P without a possibility of P response due to crop needs being met by mineralization of organic P.

From a water quality standpoint, methods for analyzing runoff are needed that determine the amount of algal available P in soluble and adsorbed form. Methods such as those recently outlined by Sharpley et al. (1991a) that identified bioavailable P (BAP) should undergo wider testing by researchers and appropriate agencies. Additionally, some method of relating soil test P to water quality is required. Investigations similar to Wolf et al. (1985) that examined the relationship between quick tests for soil, labile, and algal available P should be encouraged.

Future research should be directed towards improving partitioning of soluble, particulate, and especially bioavailable P transported in runoff and their dynamics in lakes. This should focus on the mechanism of exchange between sediment and solution P. With the accumulation of fertilizer and residual P at the soil surface, the relative importance of the present partitioning processes may need to be reevaluated. In particular, more accurate simulations of residual soil P release are needed. With the move to low-input agriculture, these improvements will enable evaluation of P transport in runoff from soils with high residual P levels in the absence of additional P inputs.

Although many models are available, it is often difficult to select the most appropriate model to obtain the level of detail of information required. Once the appropriate model is chosen, a major limitation is often the lack of input data to drive the model. This most frequently limits model use, and output will only be as reliable as data input. Because of these limitations, more research should be directed to development of a soil index, to identify soil and management practices that may enrich the bioavailable P content of surface waters.

Land management programs that minimize P loss require development. While models can provide some direction, the resource manager needs a practical method for handling P such that loss is minimized. Such a program is envisioned to encompass the amount of P in the soil and manure, soil chemical and physical properties, slope, management, time of year, etc. Efforts similar to the Phosphorus Index Core Team (PICT)

sponsored by USDA-SCS should be encouraged.

More applied work is needed on evaluating water quality impacts of individual practices that exist presently. Additionally, efforts toward developing innovative new practices should be encouraged. For example, Edwards et al. (1992) examined the best time of year to surface apply broiler litter from a water quality standpoint. Certain times of the year were clearly better than others. This information needs to be evaluated in concert with forage production requirements to arrive at times of application that are consistent with production and protection of the resource.

Research on P precipitation in manure utilizing Al, Ca and Fe compounds, as mentioned earlier, should also be conducted. If an economically feasible treatment method is found which transforms phosphate in poultry litter to an insoluble mineral that is stable for geological time periods, then application rates of litter could be based upon N loading. Efforts should be made to utilize compounds which minimize ammonia volatilization, hence, conserving N and decreasing the threat of acid rain.

Runoff studies focusing on movement of micro-organisms from land applied poultry litter into adjacent water bodies have not been reported in the literature. High counts of indicator organisms, such as that found in the streams and rivers of Arkansas, indicate there may be a potential health hazard which has heretofore received very little attention. Research needs to be conducted on the types and amounts of organisms reaching water bodies from land application of poultry manures and on BMPs to deter such movement. Filter strips, composting and/or the use of chemical litter treatments, such as alum or slaked lime, should help reduce the number of viable organisms entering the aquatic system. More research also needs to be conducted on decreasing ammonia volatilization from poultry litter, both within and outside of chicken houses. Nutrient management studies should also be conducted to determine BMPs which minimize ground water contamination from nitrate from poultry litter.

Recommendations:

Studies are needed to determine whether poultry litter application should be based on nitrogen or phosphorus loading.

Critical soil test P levels which lead to eutrophication of sensitive water bodies should be identified.

A need exists for a soil test which relates P levels in the soil to P runoff from fields.

Research on P precipitation in poultry litter using Al, Ca and Fe amendments needs to be continued. Efforts should utilize compounds which inhibit ammonia volatilization.

Studies on N dynamics and leaching, particularly nitrate leaching into groundwater, need to be conducted.

Research should be conducted to determine the amount of micro-organisms, particularly pathogens, which runoff of pastures receiving poultry litter into streams and rivers.

Models which accurately describe the fate of nutrients (particularly N and P) in poultry manure need to be developed.

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III. Swine Manure Management

Summary

Production of pork is a major agricultural enterprise in the United States, with the majority of the production in the Midwest. Manure production from all hogs based on the 1988 inventory would exceed 14.1 million Mg (15.5 million tons) with a nitrogen content of 0.66 million Mg (0.73 million tons), phosphorus content of 0.42 million Mg (0.46 million tons), and potassium content of 0.66 million Mg (0.73 million tons). Handling of manure and utilization of the manure as a resource has become a major issue with the shift in the size of production units to those over 1000 head.

The majority of swine manure is placed into anaerobic or aerated lagoons since the current large scale production systems have found these handling systems to be the most efficient for handling and storage. Manure composition from this type of storage is relatively homogeneous compared to other systems which handle manure as a solid or slurry; however, there is still a wide range in the nitrogen concentrations in the manure. Nitrogen concentrations range from 0.4% in the aerobic lagoons to 0.13% in anaerobic lagoons. These differences are due to the amount of nitrogen lost by ammonia volatilization from the anaerobic lagoons. There is little

knowledge about the effect of diet on the composition of manure because most studies evaluate the composition after storage rather than at the entry into storage.

Environmental concerns are related to both water and air quality. Water quality concerns involve both nitrate and phosphorus and little information is available on the effect of manure applications on either surface or ground water quality from either storage systems or land application methods. Likewise, the effects of manure on air quality are not well understood relative to the amount of ammonia or methane losses from storage and application and the presence of odors associated with manure handling systems. These issues need to be linked with the aspects of use of manure as a nutrient resource.

Effective use of manure as a resource will require an integrated approach to examine the effects of diet on the composition of manure, effects of storage on the loss of nitrogen, effects of handling and application method on the loss of nitrogen in the field, and the impact of manure on the quality of the environment. These issues have not been addressed as a system to evaluate the potential use of swine manure as a

other nutrients has not been investigated and will need to be studied in concert with the environmental and production issues. Economic considerations of the handling and utilization of manure will dictate the use of manure from different swine systems.

A. Introduction

Production of pork is a major agricultural enterprise in the United States, with a majority of the production in the Midwest (Ohio to Nebraska and Minnesota to Missouri) and North Carolina. Seventy-nine percent (79%) of the hogs and pigs marketed in 1987 (96.6 million head) were produced in the north central region of the U.S. (Bureau of the Census, 1989). Iowa has ranked first in hog inventory since 1980 and in 1987 was estimated to have 25.6% of the December 1 inventory of 53,795,000 hogs and pigs on farms. Inventory on farms tends to fluctuate between 50 and 70 million swine in a 4-7 year cycle period.

In 1980, 21% of the growing-finishing pigs and 45-50% of the nursing and nursery pigs in the U.S. were housed in confinement facilities (for example, liquid manure systems; VanArsdall and Nelson, 1984). With the large influx of new confinement construction, especially the construction associated with contract production units in North Carolina and Iowa, it is logical to predict a major increase in the percentage of manure captured and stored as liquid or semi-liquid.

The Corn Belt states are expected to remain the primary hog production areas although some shifts within the area will occur. Because of the historically lower feed grain prices and lower human population densities, pork production is expected to expand west of the Mississippi River, especially in the western (Kansas, Colorado and Wyoming) and southwestern fringe (Oklahoma) areas of the Corn Belt (Hurt et al., 1992).

Expansion will be governed in part by individual state laws and/or constitutional amendments regarding corporate ownership of livestock. Currently, Nebraska has an amendment to its constitution restricting non-farm corporate ownership of livestock destined for slaughter while Wyoming is utilizing municipal bonds as a source of financing to attract corporate production units. Similar differences exist among other states.

Production of pork is accompanied, as might be expected, by the production of animal waste by-products with almost all the waste returned to farm land in some manner. Estimates are that swine manure production accounts for 12-15% of the total livestock waste produced annually in the U.S. (VanDyne and Gilbertson, 1978).

Today's swine production systems have become larger, more specialized and more dependent on purchased feed supplies than in the past. Environmental problems associated with swine production during the 1950's and 1960's were often overlooked. However, swine production was characterized by small, individual systems which relied on recycling of animal manures back to the land as a major nutrient source for the farm. There have been many structural changes in the industry in the last 20 years. These have made the issue of the environmental effects of swine manure management a major planning and operation concern. The industry is rapidly consolidating. A recent University of Missouri study (Rhodes, 1990) indicates that larger production systems have the most rapid growth rate in terms of percent market share. Evidence is presented in that study which shows that only units with over 1000 head annual sales are expanding. In 1988, large units (1000 head) produced over 60% of the market hogs.

Major environmental concerns are associated with surface and ground water quality, as well as with air quality associated with odors and gaseous emissions from large scale swine production operations.

B. Manure Production And Composition

Swine manure composition may be estimated through various sources (ASAE, 1990; MWPS, 1985) and is presented in Table 1 in terms of fertilizer components available to the plant. ASAE Data (ASAE, 1990) gives estimates of daily manure production for various species, and gives means and standard deviations of physical and chemical characteristics of the manure. Swine are estimated to produce daily raw manure as much as 8.4% of body

weight (urine and feces). Sweeten (1992) recently projected that the total manure excreted from all hogs and pigs in the U.S., based on a December 1988 inventory, to be as follows:

Number of Head	55,299,000
Annual Manure Production (solids)	14.1 Million Mg
Nitrogen	0.66 Million Mg
Phosphorus	0.42 Million Mg
Potassium	0.66 Million Mg

More recent calculations indicate that the elemental phosphorus values should be 0.23 million Mg and elemental potassium should be approximately 0.37 million Mg.

Since much of the nation's swine manure can be collected, stored and spread on the land surface, these values represent a potential nitrogen fertilization of approximately one eighth of the nation's corn crop, and approximately one fourth of the total corn cropland for phosphorus and potassium if 100% of manure were recovered and applied and there was no loss of nutrients.

Even though data is not available regarding the amount of the excreted manure that can be collected, it is estimated that over 80% of the manure would be generated in systems where it would be collected. Treatment systems may remove a significant amount of nitrogen, but phosphorus and potassium are land applied.

Nutrient retention by manure from swine production units is not the goal of many producers since land for manure application is limited. Many units utilize anaerobic lagoons to digest manure solids and allow the manure to be handled as a liquid. Anaerobic lagoons can volatilize 70-90% of the nitrogen in the manure. Manure nitrogen is converted to ammonia in lagoons, where it is lost to the atmosphere. Where land is limited, anaerobic lagoons allow land requirements to be decreased to 10% of the land required for application of slurry manure.

Swine manure tends to be a relatively homogeneous material from production unit to production unit, unlike manure collected from ruminant animals. Similar to poultry, almost all the swine in the United States are fed diets formulated with corn/grain sorghum and soybean meal with the addition of vitamins and minerals. In addition to calcium and phosphorus additions, zinc is added to prevent deficiency symptoms at 50-100 mg kg⁻¹, copper at 5-10 mg kg⁻¹ and selenium at 0.3 mg kg⁻¹ (NRC, 1988). As a percentage of the total mineral content in the diet, excreted swine manure is estimated to contain 86%, 100%, 79%, 40%, 74%, 59% and 66% of the Cu, Zn, Mn, Ca, Mg, K and Na, respectively, offered to the pig (Overcash and Humenik, 1976). Currently, the FDA is holding hearings on the environmental impact of selenium additions to all animal diets (Muirhead, 1992).

The major differences in composition of manure are dependent on the methods of collection, dilution and storage and are not diet dependent. Nitrogen digestibility for corn-soybean diets is estimated to be in the range of 85% of the total N present in typical corn-soybean diets (McConnell et al., 1972). The majority of nitrogen excreted from a pig is as uric acid in the urine and organic nitrogen forms in the feces. Phosphorus will be in an organic matrix as phytic acid from the undigested phosphorus in cereal grains and other complexes as a result of growth and digestion processes and will be present in both the feces and urine. For typical corn-soybean based diets, phosphorus digestibility is estimated to be in the range of 40-60% of the total phosphorus present in the diet (NRC, 1988).

Currently, it is estimated that corn-soybean based diets supply sufficient potassium for swine of all sizes such that supplemental additions of potassium are not normally recommended (NRC, 1988). However, data are beginning to accumulate suggesting a response to potassium additions in situations that involve changing agronomic practices, changes in feed ingredient processing, and the use of alternative feedstuffs (Mabudiuke et al., 1980 and Coffey, 1987). Little data exists on the digestibility and/or retention of increased potassium in the diet. Thus, no predictions can be made as to the impact of

supplemental potassium additions (generally as potassium chloride) on the composition of swine manure.

An emerging area of research by swine nutritionists is the use of phytase enzymes in diets to enhance utilization of phytase phosphorus in cereal grains which will reduce the amount of phosphorus excreted, due in part to lower rates of dietary additions of inorganic phosphorus. Improved efficiencies of protein utilization will reduce the amount of excreted nitrogen. In the Netherlands, it is estimated that nitrogen and phosphorus excretion by pigs can be reduced by 33% and 40% respectively by the year 2000 through advances in swine nutrition (Jongbloed and Lenis, 1992).

Sodium chloride additions to swine diets have decreased over the years, partially in response to concerns about the fate of sodium in stored manure. Generally sodium chloride is supplemented in swine diets at the rate of 0.25-0.5% to prevent deficiency symptoms with 0.25-0.3% being the most common addition rate. In anaerobic storage pits, sodium ranges from 5000 to 9000 mg kg⁻¹ on a dry matter basis for dietary additions of 0.2-0.5% (Sutton et al., 1976).

As an average value for all phases of production, it is estimated that 40 kg pigs produce 182 grams of volatile solids per day with the ratio of volatile solids to total solids equal to 0.81 (Overcash and Humenik, 1976).

The U.S. industry is improving the overall conversion efficiency of the swine herd.

Current estimates of manure production and composition are based on whole herd feed conversion efficiencies of 3.7-3.8. However, many producers have made large advances in production efficiency and now report conversions of 3.3 or better. Recent advances in reproductive efficiency also mean less waste generated from sows and boars as a percent of the total waste stream. Thus, previous estimates of waste production and composition may prove to be inaccurate estimators and in many cases will overestimate both the total volume of production and the composition of the waste produced.

C. Manure Management Systems

A major change in the structure of the pork producing industry is also impacting the animal waste issue. While total pork production remains relatively constant in the U.S. (estimated 92-93 million butchers slaughtered in 1992), the number of farms selling hogs/pigs has declined from 1,273,000 in 1959 to under 200,000 in 1990 (Rhodes, 1990). By the turn of the century, the number of farms with pigs is expected to decline to slightly more than 100,000 (Hurt et al., 1992). It was estimated in 1988 that 69% of the commercial hog slaughter (U.S. origin) was from 28,700 operations.

While many of these enterprises have all their production at one site, an increasing number are involved in multi-site production, either through production contacts or ex-

Table 1. Composition mean and range of swine manure from various handling systems at the time of land application.^a

Handling System	Dry Matter	Ammonium N ^c	Total N ^c	P ^c	K ^c
Solid	%	g kg ⁻¹			
with bedding	15-20 (18) ^b	2.7-4.0 (3.1)	4.0-4.9 (4.5)	1.4-2.6 (1.8)	2.2-3.7 (3.0)
without bedding	17-20 (18)	2.2-3.6 (2.7)	3.1-4.5 (3.6)	1.0-2.0 (1.4)	2.2-3.3 (2.6)
Liquid	%	g L ⁻¹			
Anaerobic storage	2-7 (4)	2.5-3.7 (3.1)	3.4-6.6 (4.3)	.7-1.6 (1.4)	1.2-3.0 (2.2)
Lagoon	.3-2 (1)	.2-.6 (.5)	.4-.7 (.5)	.05-.2 (.1)	.2-.6 (.4)

^a Adapted from Table 4 of Pork Industry Handbook Number 25 (Sutton et al., 1983).

^b Range and mean of each value.

^c Available to the plant during the season.

panded ownership. Thus, the issue of swine manure is becoming an issue of point source production, especially as it relates to livestock ownership and responsibility for the collected material.

Swine manure is handled as a solid, semi-solid slurry, or a liquid depending on the type of housing and manure handling system used. Each of these systems has some unique features which adds complexity to the problems of manure handling and utilization.

Solid Manure Systems

Smaller production systems may make use of extensive housing systems such as pastures, open feedlots or small roofed buildings where manure is handled as a solid.

In pasture production, manure is generally utilized through pasture or forage management. Rotation grazing will allow manure to be somewhat uniformly distributed in the forage area except for watering and feeding areas. Little manure is collected and spread on other land with pasture systems. Some overloading of manure in specific areas can be expected if feed and watering systems are not moved frequently, since these areas collect a majority of the manure excreted. Pasture production systems are most common in states where smaller units are more common. Certain areas within states, such as Henry County, IL, have long-standing swine production systems utilizing pasture. Pasture production is most common in the mid and southern Corn Belt. However, it is estimated that no more than 5% of swine are now raised on pasture.

Open feedlot systems are also common with small to moderate sized production systems. These systems have exposed feedlot surfaces which are commonly covered with an accumulated manure layer. Solid manure is scraped from the feedlot surface periodically. Scraping frequency may vary from once or twice weekly to once monthly. Some manure is lost from the feedlot surface through runoff from rainfall or snow melt events. Unless some runoff containment system is in place, surface water contamination is possible if the

runoff from the feedlot can enter a water body before manure solids are settled or infiltrated into soils between the feedlot and the water body. Research has shown that 5-20% of the manure deposited on an open feedlot can be expected to be transported from the feedlot via water runoff. The fate of manure nutrients is affected by solid settling systems to contain solids. Runoff losses of nutrients are highest for potassium, and lowest for phosphorus, assuming solids are retained in a solids settling system below the feedlot. Solid storage systems are required to store manure between land disposal events. These storage facilities are generally constructed with an on-grade concrete pad with low walls surrounding the pad to allow manure to be pushed into storage and removed with a blade or a front end loader. The overall nutrient value of manure from solid systems is quite variable and nitrogen losses of 20-40% have been reported for these manure systems. Typical concentrations of nitrogen on a dry weight basis for solid manure without bedding range from 0.45-0.55% and with bedding from 0.25-0.50% at the time manure is applied to the land.

Other solid systems may utilize bedding. The most common bedding material would be straw, with wood chips or shredded newspaper as alternatives. These systems may be characterized by totally or partially roofed pens where bedding is added to absorb urine and to provide an insulation value for the animals inside unheated buildings. Manure and bedding are periodically removed from the pens, and rebedded to keep animals clean and comfortable. Bedded manure can be stored on concrete pads with optional low outside walls to help contain the bedded manure which can be stacked in a pile with a front end loader or stacking elevator.

Solid manure can be field applied using regular box spreaders or side discharge flail type spreaders. Some box spreaders require an end gate to prevent leakage of the material from the rear of the spreader during transport.

It is estimated that no more than 15% of the total swine production is accomplished with solid manure systems. These systems are most common in the western Corn Belt.

Slurry Systems

Most large scale swine production systems have totally roofed confinement systems. No bedding is used to allow manure to be handled as a slurry or as a liquid. Slurry manure has little dilution since little water is added to excreted animal manure. Liquid systems have significant water added to the excreted manure to assist with transport, treatment, and land application. Slurry manure systems are most common in the North Central Region where manure can be recycled back to cropland, and where cool temperatures are not as conducive for lagooning swine manure.

Slurry systems commonly utilize several types of storage structures. The most common system is the below floor pit covered with a slatted floor. Until recently, a high proportion of all swine confinement systems using slurry manure utilized a deep pit storage system. However, in recent years, there has been more concern over air quality problems in buildings resulting from long term manure storage in the building. Alternatives to the in-building storage system are in-ground storage tanks remote from the building, above ground storage tanks, and earthen structures. In-ground tanks may be covered or uncovered, but if left uncovered, they must have safety fence to prevent accidents. Uncovered tanks can also have the disadvantage of collecting significant snow during winter. Round tanks are becoming more popular as remote tanks, since the shape has structural advantages, and they are more easily agitated. Above ground tanks can be constructed from various materials but concrete and glass-fused steel are the most popular. Earthen structures provide the lowest cost storage system, but adequate soil investigation and construction controls are necessary to minimize ground water pollution hazards.

Slurry manure handling equipment is designed for agitation, pumping, transport, and spreading. Vacuum loading tankers are designed to provide a machine with multifunction capability. However, some systems require more agitation and pumping capacity than available with vacuum loading equipment. Agitation equipment usually consists of propeller or open impeller pumping equip-

ment. Pumps must be able to chop and pass large diameter solids in the manure. Tank type manure spreaders can be trailer or truck mounted for field distribution of manure. Direct injection equipment to immediately incorporate manure is now common. This allows immediate covering of the manure to prevent nitrogen loss by volatilization, reduces surface runoff potential, and significantly reduces odor potential.

Manure is most often applied to cropland near the swine production unit. A majority of slurry storage systems have storage capacities to handle 120-180 day storage intervals. This requires the application of manure two or three times per year. This sometimes leads to problems with having land available for manure application in the middle of the growing season or during winter conditions. One hundred eighty day storage is recommended in the Corn Belt to minimize manure application problems, and full year storage is becoming more popular.

It is estimated that 50-60% of producers use slurry manure handling systems. These units are most common in the Corn Belt.

Liquid Systems

Hydraulic flushing systems have been successfully used for twenty years for quick, efficient removal of manure from swine confinement buildings. Flushing systems require the use of larger manure storage systems since significant amounts of water are added for flushing. Anaerobic lagoons are used extensively for storage, treatment, and, in many cases, as a recycling system. Recycled treated lagoon water is often used to minimize storage requirements. In areas where lagoon water can be irrigated throughout the year, and where adequate fresh water is available for flushing, recycling is not generally practiced. Anaerobic lagoons are also popular for swine production systems with limited land base, since high losses of nitrogen can be expected in anaerobic lagooning systems. Nitrogen loading rate regulations are common for many states, so the anaerobic lagoon requires significantly lower land area for application than other manure management systems.

Anaerobic lagoons also allow the transport and application of a liquid low in solids. Conventional irrigation equipment can be used to apply anaerobic lagoon liquid to land. Even though higher volumes of waste are produced with these systems, the cost and labor requirements for application are lower per pig produced for the liquid system than slurry or solid systems.

Aerated lagoons can also be used as a storage and treatment system for flushing units. Odors are minimized and recycling is safer for disease prevention, but the cost of mechanically aerating a swine lagoon is relatively high. Capital, energy and maintenance costs have been high enough to prevent this from becoming a common waste treatment system for swine farms, even though it is common as a municipal and industrial sewage treatment system.

Odors, potential leakage, overflow and over application of lagoon effluent are the major environmental concerns associated with anaerobic lagoons. Proper design, loading and management are required to minimize odor problems. Soil investigations and proper construction techniques are required for ground water protection. Adequate irrigation equipment is needed to dewater lagoons on a regular basis. Nutrient management plans should specify loading rates to properly utilize the manure product.

Anaerobic lagooning systems do lose significant amounts of nitrogen to the atmosphere, but phosphorus and potassium are not lost. It is estimated that 80-90% of the input nitrogen is lost to the atmosphere through ammonia volatilization. A high proportion of the phosphorus is contained in lagoon sludge. Periodic cleanout of this sludge is required for continued efficient operation. These phosphorus rich sludges should be applied to land other than what is being irrigated for nitrogen management to prevent high levels of phosphorus build-up in soils where waste water is being applied.

The majority of the systems using anaerobic and aerobic lagooning systems are in warm weather climates. The majority of large operations (1000 head per year) are using an-

aerobic lagoon systems to minimize land application areas. These operations are concentrated in the South East, Southern Corn Belt and in the South West Plains. It is estimated that 20-30% of swine production uses liquid manure systems.

Issues in Manure Handling and Disposal

The major issues associated with waste management for the pork producing sector of animal agriculture are related to runoff control from open feedlots, storage requirements and land application of collected manure from confinement facilities. The runoff control questions are very similar to those of the other animal sectors.

Storage and land application problems from confined production units occur in pork production due to the large volumes of water often associated with the material. Depending on method of collection and storage, the collected material, at the time it goes into a storage device, can range from 90-99.9% water.

Generally, growing-finishing pigs from 21-100 kg live weight can be expected to generate 0.39-0.45 kg of waste per day on a dry matter basis (Brumm et al., 1980). It contains 1.9% phosphorus, 7.2% nitrogen and 3.2% potassium (expressed on dry weight basis) as by-products of the animal digestion process. Depending on the phase of production and the specific production practices of the pork producing unit, it may also contain significant amounts of copper as a result of additions of up to 250 mg kg⁻¹ copper as copper sulfate to swine diets for growth promotion. Swine manure may also contain antimicrobial drug residues as a result of dietary additions of these growth enhancing or health benefiting compounds (Brumm, 1978).

These residues have in some instances limited alternative utilizations of the collected product. For instance, high levels of copper in the waste stream are known to reduce biological activity in anaerobic storage devices (Brumm, 1978) and antimicrobial drug residues have been implicated in failures of pilot

anaerobic digesters designed to generate methane (Fischer et al., 1978).

Refeeding of collected swine manure has been researched and even tried on several commercial swine units. However, the large volumes of water associated with typical manure collection methods has meant that dewatering of some type must be employed to generate a material that was easily handled. Refeeding to a different species (generally beef) has been successful on a limited scale. The possibilities of high concentrations of copper and/or other potentially toxic elements or drug residues has limited this refeeding to beef animals during the growing stage of their life cycle. This limitation has generally minimized the concern of residues entering the human food chain through refeeding. In general, the primary safety concerns from feeding animal manure are potential harmful residues of pesticides, drugs, toxic minerals and other toxins and the hazard of disease transmission (ASAE, 1978).

Some refeeding of dewatered swine manure has been practiced to the sow herd as a means of enhancing colostral immunity for newborn pigs. Refed manure has been recognized as a possible source of internal parasite infestation and dysentery spread.

Reuse of stored swine manure as either a source of water for flushing or as a nutrient source in the diet has caused concern regarding animal health. Anaerobic storage in either deep pits or lagoons does not affect the survival of roundworm eggs, *Treponema hvod-senteriae* and *salmonella* spp.

As mentioned earlier, generation of methane has been explored as an alternative use for the collected material. In general, to be successful, methane generation relies on thermophilic bacteria for the conversion of organic wastes to volatile fatty acids and then to methane. With much of the pork production in the U.S. occurring in the north central regions, extensive investments in insulated and even heated facilities have been necessary for this bacterial process to continue during winter weather.

Summaries suggest that only 40-60% of the volatile solids are converted to methane with a practical gas production estimate of 1 m³ of methane per 0.61 kg of volatile solids converted in the digestion process (Sweeten et al., 1981). The conversion of the organic wastes to methane does not decrease the need for disposal of by-products. Removal of carbon as methane from the waste stream does not decrease the amount of nitrogen, phosphorus, potassium or other significant elements in the digester effluent.

D. Land Application Of Manure

Problems

An issue complicating the swine waste picture for many producers is the conflict of best management practices for nutrient conservation and utilization by growing crops and best management practices for soil erosion control. It has long been a recommended practice by extension specialists to incorporate spread manure into the soil surface within 24 hours after land application. This practice can significantly reduce odors and minimize ammonia volatilization.

Direct injection by means of tanker wagons equipped with injection devices has become a common technique for land application in much of the Midwest. Generally this injection, and the resultant covering of the injection slot, has resulted in soil disturbances equivalent to major tillage operations.

However, many producers, as part of their approved Soil Conservation Service conservation plan, have agreed to significantly restrict or stop any fall tillage practices as a means of maximizing residue cover at time of spring planting. Thus, land application and tillage in the fall, long an accepted best management practice for manure application, may result in a violation of the SCS plan and a reduction in government payments under provisions of the 1985 Food Security Act and the 1990 Food Agriculture Conservation and Trade Act.

Fall application of manure to cropland following harvest is often recommended because the risk of damage from soil compaction is minimized. Spring applications are usually accomplished prior to tillage and planting. Frequently in the spring, soils receiving the manure are close to saturation, resulting in significant compaction from spring application. Also, labor availability often favors fall application.

The issue of storage costs if fall application is limited must be considered. Currently, most specialists recommend and/or regulations require 90-180 day storage capacity for collected animal wastes. This capacity generally is based on the growing season for the area or state, on the assumption that collected manure will be land-applied in an appropriate manner in the spring and fall. If fall application is no longer feasible due to soil conservation concerns or possible runoff concerns, storage needs increase accordingly. This not only increases cost, but also transfers the seasonal work load to an already intense time for many producers.

For the traditional corn-soybean farmer who also raises pork and has little, if any, forage production in the cropping system, a change in cropping system may be required to provide a land base for partial utilization of the manure during summer months. How to utilize this forage, where the need is currently nonexistent, is an emerging problem for many producers.

Impact of Manure on the Soil

Application of manure to the land can supply adequate nutrients for the efficient production of grain crops. Sutton (1992) stated that the potential fertilizer value of swine manure may range from \$2.50 to \$3.50 per market hog sold. He outlined some of the potential problems which need to be addressed concerning the use of swine manure as a fertilizer. Currently, there is no rapid, inexpensive method for testing manure before it is applied to the land. Without knowledge of the nutrient content prior to application, it is difficult to apply proper rates to meet the soil

fertility requirements. Application methods also induce variability in the amount applied because of the variation in the amount of material deposited either on or into the soil.

Nitrogen supply is often thought to be the primary nutrient resource available from manure. However, there are proportionally larger amounts of phosphorus and potassium available than nitrogen because of the losses of nitrogen during the storage process. There is little information available regarding the nitrogen losses during storage, and variation in losses have been documented ranging from 10 to 90%. Application of manure in quantities required to meet the nitrogen requirements of a corn or other grain crop can lead to excessive supplies of both P and K in the soil. Manure value as a fertilizer needs to address the nutrient supply from all elements and to do this will require effective testing of the composition of swine manure. MWPS (1985) provides estimates for nitrogen losses during storage and land application (Tables 2 and 3). The following table is based on the MWPS guidelines.

Table 2. Nitrogen loss during storage and application from different manure handling systems.

System	Type	Nitrogen Lost %
Daily Scrape and Haul	Solid	15-35
Bedded Manure Pack	Solid	20-40
Anaerobic Pit	Liquid	15-30
Above Ground Storage	Liquid	10-30
Earth Storage	Liquid	20-40
Lagoon	Liquid	70-80

Table 3. Estimates for the amount of nitrogen applied that is lost within 4 days of application.

Application Method	Type	Nitrogen Lost %
Broadcast	Solid	15-30
	Liquid	10-25
Broadcast/Immediate Cultivation	Solid	1-5
	Liquid	1-5
Direct Injection	Liquid	0-2
Sprinkler Irrigation	Liquid	15-35

There are various techniques to estimate the amount of available nutrient from manure applied that year or from the previous year. This estimate will vary greatly with the type and form of manure applied to land. With solid manure or open lot manure, little nitrogen is found in the ammonia or ammonium form since much of the nitrogen in this form has been volatilized prior to land application. Slurry manures may have at least 50% of the total nitrogen in ammonium N form, which is readily available in the crop year following application. Phosphorus and potassium in manure is frequently assumed to be as available in manure as in commercial fertilizers. The key to estimating the nitrogen contribution of manure after application rests on the mineralization decay series expected from the breakdown of organic solids after land application. For swine manure, the estimated first year N contribution can vary from 25-50% of the total organic nitrogen. This is a function of the breakdown rate of solids in the soil, which is a function of particle size, shape, temperature, moisture and other environmental factors, including the level of antibiotics in the manure. However, with modern feeding systems, particle size is small, and mineralization rates approaching 50% of the organic nitrogen in the first year may be expected. The second year rate may be approximated by one half of the first year rate, approximately 25%, and the third year, one half the second year rate, 12.5%. Little additional nitrogen contribution is expected three years after application of swine manure.

There are benefits in applying manure to the soil in addition to meeting the nutrient requirements of the crop. Smaller amounts of nitrogen and organic matter contained in the manure will contribute as an energy source for microbial activity within the soil. Manures have long been recognized for promoting soil structure and aggregation; however, the mechanism of the process has not been identified. Application of manures to the soil will enhance the soil quality; however, at this time it is not possible to determine the application rates required for this effect. The lower nitrogen contents which are reported in lagoon systems may be adequate for maintaining and promoting microbial action in the soil. Soil aggregation and a stable soil structure would improve the infiltration process and would have a positive impact on surface runoff and enhance the effect of other soil conservation practices. Application of manure to the soil for the purpose of enhancing the soil may not provide sufficient economic incentive for utilization of manure as a resource.

Management of the nitrogen within manure to optimize the value as a fertilizer is not well understood. Losses of nitrogen as either ammonia or nitrous oxide, or loss of methane from the soil diminishes the value of the manure and also may impact the abundance of greenhouse gases in the lower atmosphere. There is little information on this aspect although preliminary studies would suggest that these losses may account for a significant portion of the nitrogen applied.

Application rates to the soil are dependent upon the soil, crop, climate, manure composition, and mineralization rate. Manure applications will need to be incorporated into best management practices which include both crop residue management and soil management aspects. The amount of land area needed for the effective utilization of manure will depend upon the composition of the manure resource and the treatment of the manure after application. There has been some use of nitrification inhibitors to arrest the rate of mineralization; however, these have not been fully evaluated under field conditions and the results have been variable among different studies. There is a need for coordinated research among several disciplines to fully un-

derstand the most effective manure application methods and rates for different crops and soil conditions.

Disposal of Dead Animal Carcasses

Along with the usual stream of waste associated with pork production, a new concern is the disposal of dead animal carcasses. In many states, the legal requirements for disposal are incineration, burial, or pickup by a commercial rendering service. Similar to the production sector, there has been a significant decrease in the number of dead animal rendering services in the U.S. (Fats and Proteins Research Foundation, 1992).

Because of decreased access to rendering services, increased charges for rendering services, frozen ground in winter months, and high fuel costs associated with incineration, many pork producers are evaluating composting of swine carcasses as a disposal alternative. Research is limited in support of this practice and it is unclear what the legal aspects of this practice are with regard to current state laws and local health regulations regarding dead animal disposal.

E. Environmental Quality Issues

In the past, the issues of manure application to the land have been more concerned with environmental aspects rather than with the nutrient resource. Both water and air quality are integral parts of the manure system and efforts need to be undertaken to minimize any environmental impact.

Water Quality Issues

Environmental water quality problems associated with swine production have been related to excess manure generation relative to land available for proper utilization, and to inadequate manure storage and handling facilities. Excess manure application rates, runoff and leachate from manure application sites,

and leakage and overflow from manure storage sites represent major environmental concerns. The problem of a manure surplus on swine production farms is exacerbated with available, low cost commercial fertilizers, large concentration of production units, reduced availability of labor, narrow profit margins and higher priced land.

The concept of population equivalent is sometimes used to evaluate the potential for animal production systems to create water pollution problems. However, it is incorrect to use the amount of manure generated by animals as an indicator of actual water pollution since systems are not designed or operated to discharge the waste into water bodies. Manure generation is only an indicator of the total potential pollution. Modern manure management systems can be designed and operated to meet strict discharge guidelines.

Swine manure has several water pollution components. These include oxygen-demanding materials (organic matter), plant nutrients, and infectious agents. Color and odor are potential pollutants of secondary importance. Organic matter serves as an energy source for aerobic bacteria when it enters a receiving stream. Increased bacterial metabolism resulting from a discharge of organic waste into a stream increases the oxygen depletion rate. If rate of oxygen depletion exceeds re-aeration rate of the stream, oxygen depletion occurs. Decreased or depleted oxygen levels can result in fish kills and anaerobic conditions in the stream or other water body.

Organic matter in waste water has historically been measured as biochemical oxygen demand (BOD). This is a measure of the amount of oxygen required to metabolize waste during a specified time, usually 5 days.

Chemical oxygen demand (COD) is another measure of organic strength of a waste which is based on chemical rather than biological oxidation. COD will exceed the BOD value of animal wastes since animal manure and other waste products contain organic materials resistant to aerobic bacterial degradation. COD/BOD ratios vary from 3.5 to 6.5 depending on species and feed rations.

Reduced organic substances such as ammoniacal nitrogen also increase oxygen demand, in addition to effects of organic matter. Relatively high ammonia concentrations are found in liquid manures, anaerobic lagoon effluent and open feedlot runoff. Estimates of organic strength of different animal waste flows are available in many references (for example, ASAE, 1990; Khaleel et. al., 1978; Mickle and Mazurak, 1976; and Miner et. al., 1966).

Figure 1 illustrates the relative strength of various waste streams. Note that raw manures have very high organic strengths compared to other common waste streams. However, it should be noted that with the exceptions of accidental discharge or excessive precipitation events, little, if any, waste should reach streams or other water bodies from environmentally acceptable animal production units.

Swine manures have high concentrations of plant nutrients. These nutrients are beneficial when recycled properly to land. At the same time, these same nutrients have potential to increase nutrient concentrations in waterbodies if wastes are discharged into them. Nitrogen and phosphorus are the plant nutrients of primary concern. The increased nutrient loading on streams can stimulate the growth of aquatic plants which may have significant impacts on the acceptable water quality of that stream or lake. In addition, high manure loading rates provide high levels of nitrogen which can, in turn, increase shallow ground water nitrate concentrations.

Disease transmission of water-borne organisms of animal origin is another potential water pollution hazard resulting from animal production. Several diseases can be transmitted from animal to animal and from animal to

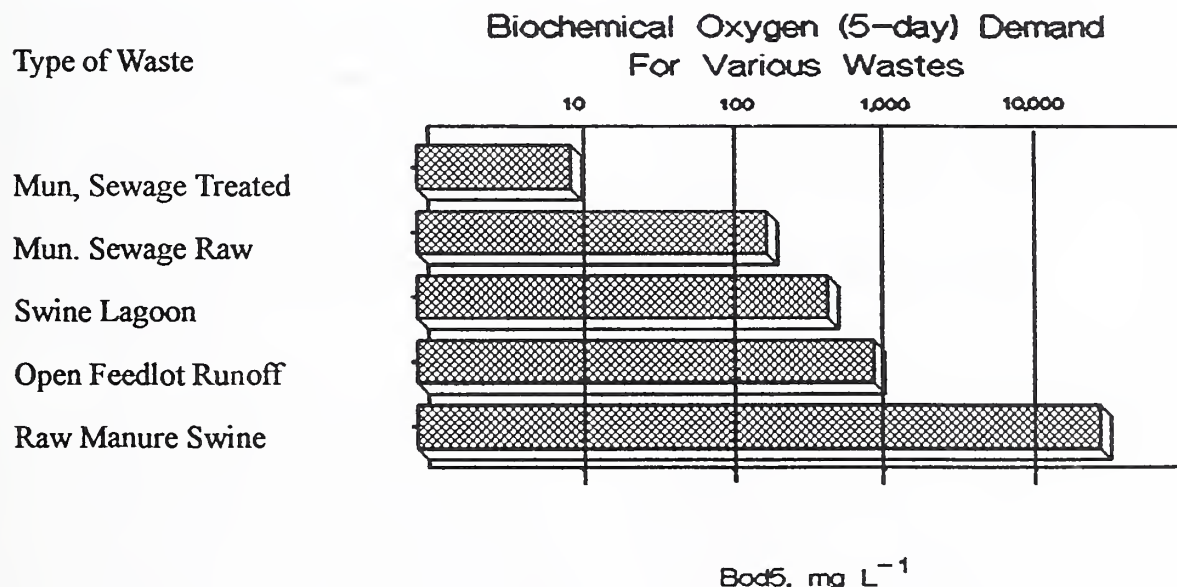


Figure 1. Approximate strength of various wastes.

human (Hensler et. al., 1970; Young, 1974). Some examples include bacterial infections of *Salmonella*, *Listeria*, *Leptospiro*, *Vibri*, *Brucella*, *Coxiella*, *Chlamydia* and *Mycoplasma*. Other fungi and protozoan infections have been identified. Modern manure management systems have to take the possibility of disease transmission through the environment into account. Prevention of improperly treated manure laden runoff water is the main defense in prevention of disease transmission.

Application of swine manure to land represents a potential surface and ground water quality problem if proper management procedures are not followed. Waste loading of swine manure discharges to ground or surface waters is not well documented except for limited research studies. The worst case scenarios for surface runoff would be surface applied manure on frozen, snow covered ground with subsequent rainfall or application of liquid manure by irrigation at rates which exceed the infiltration rate of soil. However, research indicates little manure runs off land with properly applied manure.

Environmental impacts of manure sites and application problems are only beginning to surface. Excess application rates in fields can lead to increased nitrate concentrations in shallow wells and in many areas, the concentrations often exceed 10 mg L^{-1} . The extent of these problems is not well known and generally less than 20% of the rural wells are expected to have nitrate problems; however, the depth, soil, aquifer material, and position of the well relative to any source will impact the nitrate concentrations.

Another water pollutant commonly associated with outdoor and unconfined animal production is increased sediment in surface water. Animal traffic in pastures, near and along stream banks, and on open feedlots can result in increased erosion in areas with animal production systems. Sediment is normally associated with cropland erosion, but in watersheds with significant permanent surface cover and high water quality areas, there is a potential impact of sediments resulting from animal production systems. Properly designed and operated feedlot runoff control systems

and good pasture management can significantly reduce the problem.

Air Quality Issues

Odor control has become a major environmental concern of the swine industry. Not only are units larger and more concentrated with a larger potential odor problem, but also neighboring residents have apparently become less tolerant of swine odors since the frequency of nuisance law suits appears to be increasing. Swine production is becoming more concentrated on fewer farms, while, at the same time, neighbors are now less likely to be associated with the swine industry. Swine producers have identified odor complaints as a major industry environmental issue.

Emission of gaseous wastes from production and manure storage systems has become a major environmental issue in Northern Europe during the past decade. Ammonia discharge from swine production systems is now being regulated in the Netherlands. Ammonia has been associated with acid rain problems in the region. Even though this has not yet been identified as a problem in the U.S., there could be some future implications for the swine industry. Other gases, N_2O , CH_4 , CO_2 , are all associated with greenhouse effects. Production of these gases is increased through anaerobic treatment of swine manure.

Economic Issues

A recent study by the University of Missouri (Rhodes, 1990) reports that over 50% of the nation's hogs/pigs have been marketed by farms producing more than 1000 head per year since the mid 1980's. Nearly 70% of all market hogs in 1988 came from units producing greater than 1000 head per year. In that year, 1180 operations producing more than 10,000 pigs per year marketed nearly 19% of the nation's commercial slaughter of domestic origin, while a subgroup of larger firms marketing more than 50,000 head produced nearly 6.6% of the total. A survey of expansion plans for swine operations in early 1989 (Rhodes, 1990) found that after 3 quarters of

losses by average producers, 30% of all operators were still planning for expansion. The frequency of expansion plans rose with (a) size of operation, (b) multiple production units, (c) location outside the North Central Region, and (d) units with present new facilities. Therefore, the structure of the swine production industry continues to change. New larger units are expanding outside traditional production regions. Projections are made (Rhodes, 1990) that units with less than 2000 may not be economically viable in the near future.

F. Summary

Where do possible animal welfare and animal rights fit into the equation? In most European countries, an increasing percentage of the breeding herd is being given access to straw bedding during a portion of the gestation and lactation phases of production. If the United States follows the European lead at some future time, either through legislation or consumer pressure, an entirely new set of problems is created since little information is available regarding the composition, storage or land application of this high residue waste material.

While the general trend in U.S. swine production is towards increasing confinement production, there is a growing minority of small and not so small producers who are employing intensive outdoor pig production due to the high investment costs associated with confinement production units. In addition to the obvious concern regarding surface runoff from these units, there is the issue of nutrient leaching from the intensive production area, especially if stocking rates result in total removal of all vegetation. While leaching concerns will be specific to each production site, it is of sufficient concern that the United Kingdom has begun to consider this means of nitrogen introduction into agricultural production when it designates "nitrate-vulnerable zones" (Worthington and Danks, 1992).

There are several issues in swine manure management which need to be addressed. The evaluation of the quality of the manure resource and the potential enhancement or preservation of the resource during storage and

handling will require attention since it appears that the quality is more dependent upon treatment than diet. Land application method and rate of application are crop, soil, and climate specific and attention needs to be directed toward methods which can provide a rapid evaluation of the quality of the manure as it is being hauled or applied to the field. With this type of information, the potential negative environmental impacts to either water or air quality will be negated or minimized. There are several challenges which need to be addressed in the area of swine manure management and most of the answers are available, although the linkage among the pieces has not been fully identified. Once these pieces are in place, we can effectively utilize manure as a resource.

Recommendations

There are some specific recommendations which need to be addressed to assist in the effective utilization of swine manure as a resource. These are as follows:

Evaluation of the relationship between diet and the quality of the manure.

Improved understanding of the changes which occur in manure under different handling systems and an improvement in methods to assess the composition of manure.

Evaluation of methods which can adjust the application rate of manure to compensate for changing quality.

Evaluation of the most effective methods of applying manure to preserve the nutrient resource and maintain conservation tillage goals.

Improved understanding of the utilization of manure as a resource and the economic value of manure from different handling systems.

Improved application methods which minimize the environmental impact from both water and air quality.

Improved understanding of handling and storage methods and their impact on the environmental quality of the swine housing area.

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IV. Dairy Cattle Manure Management

Summary

Methods of collection, storage, and utilization of dairy cattle manure have received increased scrutiny during the last 15-20 years. This is in response to local increases in manure quantities because of increases in milking herd size and because of heightened environmental awareness concerning adverse effects of manure on surface and ground water quality. Dairy cattle manure contains significant amounts of the primary nutrients (N, P, and K) as well as other essential plant nutrients, and hence is an excellent nutrient source for crop growth. However, if excess amounts of manure are applied beyond utilization capacity of the crops and soil, or if manure is improperly applied, losses by surface runoff and leaching can contribute to eutrophication of surface water bodies or contamination of ground water. Dairy cattle manure may also be used for methane production by anaerobic fermentation.

states to protect surface and ground water quality from impact of manure, but similar emphasis has not been placed on systems to make efficient use of the material. More scientific research is needed to gain better information on cropping systems, manure application rates, and fermentation systems for producing methane gas so that good use of the material is made while environmental quality is protected. Work is needed in preparing education/extension packages to help producers meet these goals.

The primary issue with dairy cattle manure both now and for the future is development of management systems which use the resource without adverse environmental impacts. In a number of regions, dairy cattle manure produced exceeds loading capacity of soils available for manure application. Regulations have been passed in a number of

A. Introduction

Methods of collection, storage, and disposal of dairy cattle manure have received increased scrutiny during the last two decades (Morgan and Keller, 1987). The total number of milk cows and heifers that have calved in the U.S. has decreased from 11.2 million in 1975 to 10.2 million in 1990, while average milking-herd size increased from 75.7 to 97.8 cows per herd during the same years (Agricultural Statistics 1990, 1991). The concentration of the dairy industry is illustrated in the 1991 statistics which indicate that 66% of the total cows are in the top 10 dairy states and 50% are located in 5 states (WI, CA, NY, MN, PA). Over the last 10 years the top 10 states have remained relatively constant with MI, OH, and IA dropping one place with the move of TX from ninth to sixth and the replacement of MO by WA as the state with the tenth most cows. Although a few large dairies (in excess of 1,000 heads) are located in the Northeast and Midwest, they account for a larger percentage of the cows in the South, Southwest, and Far West (Newton, 1992). One result of changes in dairy size has been that the quantity of dairy cattle manure handled per dairy farm has increased at a significant rate (Morgan and Keller, 1987). This increase, plus heightened environmental awareness of associated soil and water quality problems, has exacerbated the need for management systems which use the biomass and nutrients in the manure without creating unacceptable air, soil, or water pollution. While large-sized dairies generate large quantities of manure which are of environmental concern, states such as Wisconsin and Pennsylvania have many smaller dairies. Regardless of dairy size, however, when the land utilization area is insufficient relative to manure quantity, problems occur.

Modern dairy management includes a proper balance of feed components so that milk is produced as economically as possible while the health and vitality of the animals are maintained. Nutrients are supplied through feed derived from pasture, hay, silage, and grains. Pasturing is done on either legumes or grasses, with grazing being the oldest and most common method. "Green chopping" or hauling the pasture to the cows is sometimes

practiced. Forages used for green chopping may include any crop normally used for pasture or to make hay or silage.

Hay fed to dairy cattle may be made from legumes, grasses, or mixtures of the two. Many dairymen consider legume hay to be essential because it provides large amounts of high quality proteins and calcium, along with liberal quantities of vitamins A and D (Coletti, 1963). Alfalfa is the most popular legume hay, while red, alsike, and crimson clover are also excellent sources of roughage for dairy cows. Hay made from grasses is generally inferior to legume hay (Coletti, 1963).

Silages are used extensively as feed for dairy cattle. They provide succulent feed during the winter months when cows are restricted to dry roughage, make possible the utilization of the entire plant without much loss during bad weather, and can be used as a source of reserve feed during the summer months. The primary silage crop is corn, although acceptable silage can be made with sorghums. Silage also can be made from alfalfa, various clovers, soybeans, pasture mixtures, and oats or other small grains.

Dairy cattle often spend portions of their time in pasture areas, feeding and lounging barns, and milking parlors. From an environmental standpoint, manure dropped in all of these locations may be of concern. However, unless too many cattle are pastured per area of land, or cattle are allowed free access to streams, lakes, or ponds, manure dropped in pasture areas may be of less environmental concern than that from the barns and milking areas. Manure dropped by cattle while in the feeding and lounging barns and milking parlor is in effect a point source of nutrients which must be utilized. Water added from cleaning of tanks or utensils in the milk house also contributes to the total waste load.

Dairy cattle manure is a complex material containing feces, urine, bedding, rain or other water, and milk house or washing wastes (Midwest Plan Service 18, 1975). This material contains all of the macro nutrients needed for crop growth with particularly high amounts of nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca). In addition to

its' nutrient value, application of dairy cattle manure to cropland is known to improve soil organic matter and tilth (Christensen et al., 1981; Klausner et al., 1974). Surface runoff from dairy feedlot and holding areas has high water pollution potential. Also, mismanagement in the land application of dairy cattle manure has been documented as a cause of water pollution. Both P and N contained in the manure may contribute to eutrophication of surface water bodies. Dairies are often located in regions where land accessibility for manure application is restricted during large portions of the year due to cropping patterns and climate. Therefore, the land application rate of animal manure or liquid from lagoons or holding ponds may often be greater than normally recommended for meeting crop nutrient requirements. Odor from lagoons, holding ponds, or surface application of manure is also an environmental concern.

Proper management of dairy cattle manure for the individual farmer involves integrating dairy herd size, available land, topography, climate, soil type, and financial resources to determine a "best" system. Alternatives to land application include composting, refeeding, and production of methane gas via anaerobic fermentation. Overall, dairy operations throughout the United States ideally must use the nutrients and organic matter from the manure to reduce fertilizer and energy costs, while at the same time using treatment systems which do not have negative effects on air quality, surface water bodies, or ground water quality.

Table 1. Manure production and characteristics as excreted. Values are approximate. The actual characteristics of a manure can easily have values 20% or more above or below the table values. The volume of waste that a waste handling system has to handle can be much larger than the table values due to the addition of water, bedding, etc.

Animal	Size kg (lb)	Total manure production				Density kg m ⁻³ (lb ft ⁻³)	Nutrient content					
		kg day ⁻¹ (lb day ⁻¹)	hL day ⁻¹ (ft ³ day ⁻¹)	L day ⁻¹ (gal day ⁻¹)	Water %		TS kg day ⁻¹ (lb day ⁻¹)	VS kg day ⁻¹ (lb day ⁻¹)	BOD ₅ kg day ⁻¹ (lb day ⁻¹)	N kg day ⁻¹ (lb day ⁻¹)	P kg day ⁻¹ (lb day ⁻¹)	K kg day ⁻¹ (lb day ⁻¹)
Dairy cattle	68 (150)	5.4 (12)	0.05 (0.19)	5.7 (1.5)	87.3 -	994 (62)	0.7 (1.6)	0.6 (1.3)	0.12 (0.26)	0.03 (0.06)	.004 (.010)	.018 (.040)
	114 (250)	9.1 (20)	0.09 (0.32)	9.1 (2.4)	- -	- -	1.2 (2.6)	1.0 (2.1)	0.20 (0.43)	0.04 (0.10)	.009 (.020)	0.32 (.070)
	227 (500)	18.6 (41)	0.19 (0.66)	18.9 (5.0)	- -	- -	2.4 (5.2)	2.0 (4.3)	0.39 (0.86)	0.09 (0.20)	.016 (.036)	.064 (.140)
	454 (1,000)	37.2 (82)	0.37 (1.32)	37.5 (9.9)	- -	- -	4.7 (10.4)	3.9 (8.6)	0.77 (1.70)	0.19 (0.41)	.033 (0.73)	.122 (.270)
	636 (1,400)	52.2 (115)	0.52 (1.85)	52.6 (13.9)	- -	- -	6.6 (14.6)	5.4 (12.0)	1.08 (2.38)	0.25 (0.57)	.046 (.102)	.172 (.380)

Source: American Society of Agricultural Engineers, data adapted from Committee S&E-412 report AW-D-1. Revised 6-14-73

Density = best estimate, not ASAE data

TS = total solids

VS = volatile solids

BOD₅ = the oxygen used in the biochemical oxidation of organic matter in 5 days at 68 F. A standard test to assess wastewater strength

N = total nitrogen

P = total phosphorus

K = total potassium

B. Manure Production And Composition

Dairy cattle normally spend a large portion of their time in the feeding and lounging barn, milking parlor, and pasture areas, and deposit a large portion of their manures in those areas (Westerman and Overcash, 1980). Manure dropped in pasture areas may or may not be of environmental concern, depending on herd size, pasture area and location, and amount of time the animals spend in the area. The major source area for dairy cattle manure which must be handled, stored, and treated or utilized is the building complex of feeding barn, lounging barn, and milking parlor.

The daily manure production, feces and urine, per 454 kg (1,000 lb.) of body weight for Holstein cows is approximately 34 kg (75 lb.), of which about 70% or 24 kg (53 lb.) is solids, and 30% or 10 kg (22 lb.) is liquid (North Carolina Agricultural Extension Service Circular 568, 1973). On this basis, the daily manure production of a mature Holstein cow weighing 636 kg (1400 lb.) is about 48 kg (105 lb.) or 0.45 h L (1.6 cu ft.). The properties of dairy cattle manure depend on several factors: digestibility, protein, and fiber contents of rations; and animal age, environment, and productivity. Table 1 shows estimates of daily manure production and manure properties for a range of animal sizes as taken from Midwest Plan Service - 18 (MWPS-18, 1985). Other sources of information on the properties of raw or liquid dairy manure include the Canada Animal Manure Management Guide (1979), Ghaly et al. (1986), and Van Horn (1990). Multiplying estimates of annual per animal dairy cattle manure production from Van Dyne and Gilbertson (1978) and the 10.2 million milk cows and heifers that have calved as of 1990 results in an estimated national annual dry weight of voided manure of 2.2×10^7 Mg. The estimated nutrient content of this material is 7.1×10^5 Mg N, 1.2×10^5 Mg P, and 5.7×10^5 Mg K (Van Dyne and Gilbertson, 1978). After losses during storage, transport, and application, the economically recoverable amounts of these nutrients can be estimated as 4.2×10^5 Mg N, 1.0×10^5 Mg P, and 4.9×10^5 Mg K (Van

Dyne and Gilbertson, 1978). The monetary value of this material on a national basis can be calculated based on total amount and current prices for commercially prepared N, P, and K fertilizers.

The actual composition of any particular batch of dairy cattle manure as removed from the milking parlor, feeding, or loafing areas will depend on the amount of moisture, the amount of bedding material present, and the rations fed. Incorporation of bedding with the manure increases the total solids content while water added during washing dilutes the material.

C. Manure Management Systems

Dairy cattle are housed in buildings using either stanchions or free-stalls. In barns with stanchions, the forward and backward movement of the cattle is limited. Manure from stanchion barns is allowed to collect in gutters where it is manually or mechanically scraped and stacked in storage areas until it can be hauled to fields for spreading and utilization (Merkel, 1981). Farmers with stanchion barns generally use bedding such as sawdust, straw, or wood shavings for the animals. Manual or mechanical scraping of the manure from the rear of the stall or the main alley into a collection gutter is generally done daily.

Characteristics of stacked stanchion barn manure depend upon the time of storage, environmental conditions, and the type and amount of bedding used. Average values for stacked and stored dairy cattle manure are 50 kg day⁻¹ animal⁻¹ produced with 4100-6900 mg L⁻¹ total N, 700-2500 mg L⁻¹ NH₃, and 3800-6900 mg L⁻¹ P (Cramer et al., 1971). Liquid wastes seeping from the stacked manure average 4.5-11.0 L day⁻¹ cow⁻¹ with 1200-2900 mg L⁻¹ total N, 780-2200 mg L⁻¹ NH₃, and 64-500 mg L⁻¹ P.

Manure produced from dairy cows housed in free-stall barns can be scraped by a front-end loader and stacked in a storage area for later utilization. In many of the newer set-

ups, the manure is flushed by large volumes of water discharged a few times a day (Merkel, 1981). The liquid waste from the flushing aisle is generally discharged to a series of lagoons for treatment. Effluent from the lagoon may be used as the flush water.

Manure collected by either scraping or flushing generally goes to a storage area. In some systems manure is immediately spread without storage, but this is not appealing to many dairymen, primarily because of frequency of disposal. Transport of manure from the storage areas is dependent on the flow characteristics of the material. Dairy cattle manure can be classified as semisolid, semiliquid, or liquid (Sobel, 1966). Semisolid manure will not flow with perceptible movement unless given mechanical assistance. Most fresh manure is in this category, and unless flushed, must be manually or mechanically transported. Semiliquid manure is material that has undergone dilution. The manure will slowly flow without mechanical assistance and contains between 5 and 15% total solids concentrations (Merkel, 1981). Liquid manure generally contains less than 5% total solids concentrations (wet basis) and is associated with feedlot runoff and effluents from milking parlors and treatment systems.

Dairy cattle manure in a solid or semi-solid state can be transported mechanically by means of front end loaders, conveyors, augers, or piston pumps. Hydraulic transport is generally used for handling liquid dairy cattle manure. Considerable information is available on the flow principles involved in hydraulic transport of liquid dairy cattle manure and calculations necessary for designing systems which move the material via open channels or pipes (Merkel, 1981; MWPS-18, 1985).

Alternative manure management systems from the initial storage facility include spreading in solid form, spreading in liquid form, immediate irrigation, and lagooning and irrigation. Storage and spreading in solid form usually has short-term storage between the time of collection and land spreading. Land spreading in the liquid form has two major disadvantages; (1) cost of the system, and (2) odors associated with agitating and field

spreading partially decomposed manure. Systems which use liquid from the initial storage area for irrigation also have the disadvantage of short-term storage availability, and hence wastes must be applied daily by irrigation regardless of weather conditions. Irrigation systems from lagoons allow for long-term storage and treatment of the waste prior to land application.

Liquid manure disposal systems for dairy cattle require separation of the liquid and solids fractions. Separation of settleable or suspended solids may be accomplished by gravity or employing mechanical devices. Gravitational separation includes sedimentation and flotation using tanks or lagoons; mechanical means include liquid cyclones and screens. Use of screens is attractive to dairy operators for three reasons (Moore et al., 1975): (1) reduction in plugging of liquid handling equipment such as pumps, piping and sprinkler nozzles, (2) reduction of the biological loading on following treatment components, such as anaerobic and aerobic lagoons, and (3) separation of solids that can be recycled for bedding or feed. The hay, hay ledge, silage, or other fibrous material removed from the manure by separator can be used as bedding material (Fairbank et al., 1975). Use of solids for bedding may negatively affect herd health (mastitis) and hence has had limited acceptance (Newton, 1992). These solids can be composted to reduce the level of mastitis-causing organisms in the bedding.

Following separation of liquids and solids from the manure, the liquid portion is commonly transported to stabilization ponds (lagoons). In these ponds beneficial organisms stabilize the material so that it can be spread on the land or used as flush water for a recycle cleaning system.

Stabilization ponds can be classified according to the mode of degradation; aerobic, facultative, or anaerobic. Aerobic lagoons are aerated so that organic matter is oxidized by bacteria supported by free molecular oxygen. Aeration is most commonly supplied by mechanical aerators which provide sufficient agitation to ensure complete mixing.

Facultative lagoons provide an aquatic environment in which photosynthesis and surface oxygenation supply an aerobic zone in the upper strata, a facultative zone throughout the central portion, and an anaerobic sludge layer at the bottom. The heavier suspended solids including biologically formed floc settle on the bottom and undergo anaerobic decomposition. Many lagoons used for treatment of dairy cattle manure were originally classified as aerobic, yet, in fact, they are truly facultative in nature (Merkel, 1981).

Anaerobic lagoons are stabilization ponds that can carry on the degradation of organic matter without the availability of free molecular oxygen. Under anaerobic conditions, the microbial population derives its energy for cell synthesis by reducing oxidized compounds such as NO_3 , SO_4 , and carbohydrates. Reduction of NO_3 under anaerobic conditions is denitrification, and considerable N may be lost by this process. For denitrification to occur in anaerobic lagoons the treatment system must have components where NH_4 is oxidized to NO_3 prior to entering the lagoon. Both facultative and anaerobic bacteria are present in anaerobic lagoons. When dairies have two lagoons, the first one generally is anaerobic and also serves as a settling basin, and the second one is facultative or aerobic using a mechanical aerator.

In order to properly manage dairy cattle manure and conserve N for later use, it must be known where N losses occur. High levels of NH_3 in freestall dairy barns have been measured, suggesting that manure in such barns might lose substantial quantities of N (Miner et al., 1975). The loss process is through hydrolysis of urea in the urine to NH_3 which is then easily lost by volatilization (Salter and Schollenberger, 1939). Work by Muck and Steenhuis (1981) indicates that when barn temperature is greater than 20°C , and barn alleys are scraped only once a day, 80% of the urea N, which is approximately 40% of the total N in the manure (urine plus feces) is lost by volatilization. The greatest N loss probably occurs on the barn floor from the time dairy manure is produced until the time it is spread (Muck and Herndon, 1985).

Manure can be stored for months in bottom-loaded storages with N losses of less than 10% (Safley, 1980, and Muck et al., 1984). Nitrogen losses from anaerobic lagoons and storages have been studied by several investigators (Willrich, 1966; Koelliker and Miner, 1973; Smith et al., 1971; Jones et al., 1973; Booram et al., 1975; Safley, 1980, 1981; Safley and Westerman, 1981). However, the wide range of reported results does not provide an accurate basis for comparing one storage design with another. Bottom-loaded manure storage, because of its crust, is generally believed to conserve N better than a top loaded storage (Muck and Steenhuis, 1981).

The Midwest Plan Service - 18 Livestock Waste Facilities Handbook (1985) gives estimates of typical N losses between excretion and land application as adjusted for dilution based on the waste handling system. For solid systems, estimated losses for daily scrape and haul, manure pack, or open lot are 15-35, 20-40, and 40-60%, respectively. Estimates of N losses during land application from this same reference based on application method are 15-30% for liquid broadcast, 1-5% for both solid and liquid broadcast with immediate cultivation, 0-2% for knifing of liquid, and 15-35% for sprinkler irrigation of liquid.

Proper utilization of dairy cattle manure also requires an understanding of where P and K losses occur. Phosphorus and K losses are considered negligible except for open lots or lagoons (MWPS - 18, 1985). About 20-40% of the P and 30-50% of the K can be lost by runoff and leaching in open lots. However, much of the P and K can be recovered by runoff control systems such as settling basins and holding ponds. Up to 80% of the P in lagoons can accumulate in bottom sludges and is not applied to land unless the sludge is removed from the lagoons.

D. Land Application Of Manure

Land application of animal manure has been practiced for centuries in the temperate

zones. The practice developed partly because there was no other place to put the material, but also because of the agronomic benefits. Application methods for dairy cattle manure depend on the fluidity of the material. Fluid manure containing less than 5% solids can be handled by most irrigation systems (Midwest Plan Service 19, 1975). The fluid material is typical of feedlot runoff or effluents from a lagoon system or milk house. The type of irrigation system selected depends upon topography, soil type, and cropping practice. Disadvantages of irrigation include: a high initial investment, operating costs for pumping, the necessity of good management to avoid runoff or ground water pollution, high labor demand with low-cost irrigation equipment, odor problems, and NH_3 loss by volatilization.

Liquid manure with 4% solids or less can also be applied to land via surface spreading. Material from pipeline systems can be spread by gravity using open ditches, flat irrigation tubing, or gated pipe. Types of surface irrigation for dairy cattle manure in the surface spreading category include border irrigation, furrow irrigation, corrugations, and wild flooding. In all cases the material should not be applied to a wet area. The system also should be shut off before water reaches the low end of the field to eliminate runoff. Of the four types of land spreading systems for dairy cattle manure, wild flooding has the most uneven water distribution (Midwest Plan Service 19, 1975).

Semisolid dairy cattle manure with 4-15% solids can be applied using manure guns or tank wagons. Large-bore irrigation nozzles can handle heavy slurries (up to 15% solids) as well as liquid materials with low solids content. These large sprinklers generally have a capacity of $23 \text{ to } 91 \text{ m}^3 \text{ hr}^{-1}$ (100 to 400 gm) and can cover from 0.2 to 0.8 ha (0.5 to 2 ac) at a setting (Midwest Plan Service 19, 1975). Tank wagons are available for transporting fluid slurries in capacities ranging from about 1.6 to 11.3 m^3 (415 to 3000 gal). Slurries must be agitated in the storages before they can be satisfactorily pumped into tankers. Tank wagons may either apply manure to the soil surface or inject into the soil with chisel-type injector shanks or mold board plow attachments. Injection is desirable both for

conserving nutrients and to reduce odor problems.

Manure with 20% or more solids is generally handled as a solid. Most solid manure spreaders are box type, although open-tank spreaders are available. Ideally, manure should be distributed evenly to the land, but the effectiveness of this depends on the characteristics of the material being spread.

Correct land application of dairy cattle manure should include crediting of the fertilizer value of the material. Dairy cattle manure management system designs are generally based on N excretion loads for a dairy and accepted land application rates for N. This is because the total N content of the manure is higher than total P, plus with the exception of very sandy soils P tends to bind to the soil particles and hence is primarily of environmental concern only if erosion occurs.

The most effective method for gauging the nutrient content of the manure is to have samples analyzed by a commercial or university laboratory. Large farm-to-farm variation can occur in nutrient content due to storage, handling, livestock feed, or other farm management differences. Unfortunately, laboratory analyses are not always convenient or available. As a consequence, procedures for crediting animal manures including dairy cattle manure have been developed by a number of different investigators including Bundy et al., (1992), Wolkowski (1992), and Good et al., (1991). These methods involve calculating the total nutrient credit for the manure using the product of the amount applied in tons or gallons, and the nutrient content from standard tables. Midwest Plan Service - 18 (1985) gives the approximate fertilizer value of solid dairy manure as 4.5 kg Mg^{-1} (9 lb. ton^{-1}), $.9 \text{ kg Mg}^{-1}$ (1.8 lb. ton^{-1}), and 4.2 kg Mg^{-1} (8.3 lb. ton^{-1}), for N, P, and K, respectively. For liquid pit manure the approximate fertilizer value for N, P, and K, respectively is 2.9 kg kL^{-1} ($24 \text{ lbs } 1000 \text{ gal.}^{-1}$), 0.9 kg kL^{-1} ($7.9 \text{ lb. } 1000 \text{ gal.}^{-1}$), and 2.9 kg kL^{-1} ($24 \text{ lb. } 1000 \text{ gal.}^{-1}$). The approximate value of lagooned dairy manure is 0.5 kg kL^{-1} ($4 \text{ lb. } 1000 \text{ gal.}^{-1}$), 0.2 kg kL^{-1} ($1.8 \text{ lb. } 1000 \text{ gal.}^{-1}$), and 0.5 kg kL^{-1} ($4.2 \text{ lb. } 1000 \text{ gal.}^{-1}$) for N, P, and K, respectively (MWPS-18, 1985).

The nutrients contained in dairy cattle manure (other than as lagoon effluent) are not immediately available to crops, but are released over time. The rate of release depends upon the amount of organic matter applied along with nutrient content, climate, and soil type. Wolkowski (1992) indicates that the N credit increases each successive year of application (up to three consecutive years) by approximately 30%. Midwest Plan Service - 18 (1985) indicates that organic N released by mineralization during the second, third, and fourth cropping years after initial application is usually about 50%, 25%, and 12.5%, respectively, of that mineralized during the first cropping season. Their worksheet requires calculation of the residual N released by mineralization from previous years as part of the overall N budget. Nearly all of the P and K in manure is available for plant use the year of application. After a few years of regular waste applications, the amounts of P and K available are about the same as in one year's application (MWPS-18, 1985). In warm, humid locations with well aerated, sandy soils, mineralization is rapid and essentially complete in 1 year. However, when manure is applied to grain crops at planting the availability of N from mineralization does not correspond to plant needs over the season. Thus the same mineralization processes occur, regardless of location, but the time frame can be compressed due to warm, humid conditions or extended by cold, dry conditions.

Use of available worksheets to credit dairy cattle waste applications involves calculating the nutrient requirements of the crop and then determining the amount of land necessary to utilize all of the available waste. Applying manure to meet N requirements more than adequately meets crop needs for P and K (MWPS-18, 1985). Over time this may cause high accumulation of P, K, and salt in the soil. The economic value of manure fertilizer can be calculated from its available N, P, and K at commercial fertilizer prices. The equivalent values will change over time as the costs of commercial fertilizer and handling practices change.

One concern with manure applications is soil salinity. Heavy manure applications can increase soil salinity, especially in arid re-

gions where little or no leaching occurs. Salts can inhibit plant growth and depress yields. Sodium and potassium can alter soil structure and reduce water movement rates. Use of heavy manure wagons can also affect yields by compacting wet soils.

E. Alternative Uses Of Dairy Manure

Utilizing the energy from animal manure has recently been given considerable attention with regard to biogas generation. Methane production from livestock manure has been shown to be an easily established fermentation process (Stafford et al., 1980; Van Brakel, 1980) and one third of the total energy content is released in the form of methane (Sobel and Muck, 1983). Hashimoto et al. (1979) and Hill (1982) report that although dairy cattle manure is less readily biodegradable than beef, poultry, or swine manure, the potential for methane production and the benefits of its use on dairy farms are substantial. A more problematic aspect of using dairy cattle manure is the large fraction of settleable and floating solids, causing difficulties in pumping the liquified manure, as well as accumulation of solids in the base of the reactor vessel (Abeles et al., 1978; Bartlett et al., 1977, 1980; Ecotope Group, 1977).

Anaerobic digesters have been successfully used to produce methane in the psychrophilic (below 20° C) (Lo and Liao, 1986), mesophilic (30 - 40°C) (Lo et al., 1984 and 1986; Erdman, 1985; Summers et al., 1987) and thermophilic (50 -60°C) (Wohlt et al., 1990) temperature ranges. Major concerns about using dairy cattle manure to produce methane which are not yet fully answered include: (1) the necessity for mixing; (2) process controls for daily operation which minimize management time and provide the operator with sufficient warning of impending biological upset; (3) the impracticality of long term methane storage; and (4) the effects of antibiotics (Midwest Plan Service 284, 1982). The land area needed for utilization of dairy manure nutrients is not reduced by digester systems as the total amounts of N and P remain in the digester effluent.

Two other alternative uses for dairy cattle manure are composting and refeeding. Composting is a process in which the volatile solids are digested by aerobic microorganisms. Because the process is aerobic, it is relatively free of offensive odors. Dairy cattle manure from stanchion or free-stall barns is considered to be an attractive material for composting because the addition of the bedding brings the material to a favorable moisture content. Stable compost can be obtained in 19-56 days depending on moisture content, air distribution, and temperature (Willson and Hummel, 1972). The primary potential benefit of composting is that a value-added product is produced. This product (compost) may then find uses off the farm where it was produced, such as in the horticulture industry. Research on the feeding value of screened manure solids (SMS) obtained from dairy cattle has shown that the SMS were lower in crude protein and higher in lignin and other fiber constituents than the manure prior to screen separation (Johnson et al., 1974a, 1974b). Digest ability and feeding trials have shown that dairy cattle can successfully use this recycled material when included as a small percentage of the diet (Southern Cooperative Series Bulletin 242, 1979). However, the solids are a low quality feed ingredient which limits their use to non-lactating cows or heifers, and hence limits overall usefulness of the material (Newton, 1922). Although methane generation, composting, and refeeding have been shown through research to be successful using dairy cattle manure, none of these techniques are currently being utilized on a scale sufficient to make regional or national impact (Newton, 1992).

F. Agronomic And Environmental Effects

Application of dairy cattle manure to land affects both the physical and chemical properties of the soil. Manure application, regardless of form, has been shown to improve tilth, increase water holding capacity, lessen wind and water erosion, improve aeration, and promote beneficial organisms (MWPS-18, 1985). When manure is applied to the soil surface, it tends to help prevent soil crusting.

When injected or mixed with the soil the manure decomposes more rapidly and the products of decomposition improve soil structure and the general physical condition of the soil (North Carolina Circular 568, 1973). Application of dairy cattle manure to cropland increases the organic matter content of the soil which in turn improves long-term aggregate stability and decreases bulk density. The result is increased infiltration. Unger and Stewart (1974), Kumar et al., (1985), and Sommerfeldt and Chang (1987) all noted an improvement in soil water retention in the 0-15 bar potential range for soils receiving manure application.

Dairy cattle manure contains significant amounts of the primary plant nutrients (N, P, and K) as well as other essential plant nutrients including Ca, S, Mg, and Cl. Animal manure was one of the earliest sources of plant nutrients, and considerable research has been done on using dairy cattle manure for crop production (Southern Cooperative Series Bulletin 242, 1979). Use of dairy cattle manure has often been done with disposal of the material as the first objective and utilization as a resource a secondary concern. The primary objective in using dairy cattle manure should be safe, pollution-free recycling of the manure nutrients. Considerations for proper use of dairy cattle manure should include the texture and fertility level of the soil; the nutrient requirements of the crop to be grown, the nutrient contents of the manure, and local climatic factors which will affect the fate of each of the major nutrients. Dairy cattle manure is commonly used for corn production (Beauchamp, 1986; Safley et al., 1984) and grasslands (Hubbard et al., 1987; Hubbard et al., 1991).

The major environmental concern with land application of dairy cattle manure is possible contamination of surface and ground waters with excess N and P. Heavy loadings of dairy cattle manure have been linked to eutrophication of surface water bodies. Phosphorus is the primary concern for eutrophication, although N may also contribute to this problem. One area of the country where eutrophication has been clearly linked to dairy cattle manure is Lake Okeechobee, FL. Since the early 1970s, dairies north of the lake have been

cited as the prime source of P (Sauber, 1989). Nitrate leaching is the primary concern with ground water. Both Hubbard et al. (1987) and Sewell (1975) observed $\text{NO}_3\text{-N}$ leaching to shallow ground water where excess quantities of dairy cattle manure were applied.

Problems with dairy cattle manure may also occur from surface runoff and leaching in feedlot or land application areas, or by leakage from lagoons. Rainfall induced surface runoff may carry urine and feces into adjacent streams, rivers, or lakes. Hubbard et al., (1987) showed that as land application rates increased, proportionately more N was lost by surface runoff than by leaching. Dairy cattle manure applied to the soil surface is immediately available for movement by surface runoff, particularly if it has been applied to frozen land. During the spring thaw and snow melt nutrients from manure may move freely with runoff.

Applied dairy cattle manure need not be an environmental problem relative to water quality. It is a problem in situations where the application rate is greater than the assimilative capability of the soil and crops, or where it is left on the soil surface rather than being incorporated and hence is subject to movement by surface runoff. The application rates may exceed assimilative capacity of the soil when the land area available for manure application is too small relative to the number of cattle or where manure is repeatedly applied to fields closest to the barns or feeding areas. Another scenario which has caused dairy cattle manure to have negative impacts on surface and ground waters is management systems which apply commercial fertilizers without crediting the applied dairy cattle manure. Unfortunately, at this time there are major dairy operations which do not credit their manure applications when calculating commercial fertilizer application rates. A contributing cause to environmental contamination from dairy cattle manure is the need to get rid of the material on a daily basis. Since milking and feeding areas must be cleaned daily, manure that is generated must go somewhere. Once the holding tank or lagoons are full this material must be applied to land regardless of weather, soil, or crop conditions.

Air quality within or surrounding dairy facilities or where manure is land applied is also a concern. Odors can be a nuisance to producers and cause complaints and even lawsuits from neighbors. Organic compounds - from uncontrolled decomposition of manure include odorous gases such as amines, amides, mercaptans, sulfides, and disulfides (MWPS-18, 1985). Noxious gases can irritate both livestock and operators, and be harmful and even lethal. Preventing production and accumulation of gases in the livestock area is accomplished through frequent cleaning of floors, avoidance of overfilling storage tanks, avoiding manure storage periods longer than 6 months, and providing adequate ventilation. Immediate plowdown or injection of field spread wastes will reduce odors.

A relatively new air quality concern is the emission of greenhouse gases from livestock manure sources. Methane losses from all livestock manure sources account for 37% of all greenhouse gas emissions from U.S. agriculture based on carbon dioxide warming equivalents (Center for Rural Affairs, 1992). The manure management system is critical in determining the amount of methane emissions. Approximately one-fifth of all methane from U.S. livestock sources is derived from anaerobic lagoons.

G. Issues And Options

The primary issue with dairy cattle manure is development of management systems which economically use the manure resource without adverse environmental impacts. Treatment systems currently are in place on most dairy farms. However, a fairly consistent philosophy at this time is that this material is a waste; i.e. something to get rid of, and the material is disposed of without careful attention to matching crop, soil, and environmental constraints to the manure stream. There is ample evidence however that, if properly managed, the nutrient value of dairy cattle manure can be properly utilized with economic profitability and environmental protection.

Government regulations have been passed and are enforced in a number of states to protect surface and ground water quality

from adverse impact by dairy cattle manure. These regulations may specify certain land utilization areas in relation to number of cows, and also require monitoring wells. For example, the state of Texas requires that producers milking herds of more than 250 cows, have a permit stipulating that dairies have no nutrient discharge. In south Florida the state's Department of Environmental Regulation reviews permit applications with the goal of balancing dairies' nutrient use and discharge. Producers are required to have adequate land disposal resources for manure (Sauber, 1989). One weakness of such regulations is that in some states they apply only to new dairies or dairies over a certain size, and hence do not protect surface and ground water quality from existing and/or smaller operations.

As discussed within this report there are a number of different options for utilization of dairy cattle manure without adverse environmental impact. Education and transfer of these technologies to dairy producers is critical so that the manure can be used for nutrients and/or energy, and that the material will be viewed as a resource rather than a waste. With a resource philosophy and best management practices, government regulatory standards on air and water quality should be able to be met in most cases. Also, use of the manure as a resource should lower commercial fertilizer and/or energy costs and hence result in improved cost/benefit ratios as compared to earlier manure disposal practices.

H. Needs

Research is needed to improve best management practices for efficient and safe utilization of dairy cattle manure. Such research includes: improved methods for reducing N losses from manure while in the barn or in storage; improved technologies for using the manure for energy; techniques for more uniformly and efficiently applying it to land; cropping systems that efficiently use the manure while providing feed for dairy cattle; and development of guidelines for amount of manure that can be applied for crop growth without adversely affecting air quality, surface water or ground water quality. The most critical information needed at this time pertains to

loading rate guidelines. Current research with a triple cropping system (Coastal bermuda-grass, abuzzi rye, and corn) at Tifton, GA, is determining environmentally safe and economically sustainable liquid dairy manure application rates by center pivot. This information can only be developed by simultaneously determining both crop response and water quality under a range of manure application rates (Hubbard et al., 1991; Vellidis et al., 1991; Williams et al., 1991). Similar research is needed with other cropping systems over a range of soil and climatic conditions.

Concerns about environmental impacts of dairy cattle manure have caused changes in both laws and management practices in a number of states. In some states new laws now require best management practices including monitoring surface and ground water quality. This has resulted in new dairies purchasing more land on which to utilize the manure than was previously common practice, and in some states dairies which were unable to meet environmental standards have either moved or gone out of business. Along with the research needs, education-extension packages are required to aid both existing and new dairies in developing cropping and manure utilization systems which meet environmental standards. Recent extension publications from Wisconsin (Bundy et al., 1992; Good et al., 1991; and Wolkowski, 1992) are good examples of information for dairy producers which show how to credit manure applications for nutrient management and protection of water quality. Similar information is needed so that dairy producers in all states will view manure as a resource.

Along with research and education/extension packages, economic incentives are needed to get widespread utilization of dairy cattle manure. A program in Lancaster County, Pennsylvania, currently connects manure generators with interested buyers and could serve as a country-wide model (BioCycle, 1992). Farmers are purchasing the manure as a replacement for commercial fertilizer with some of it going as far away as 500 km from the source. Economically the marketing area is generally limited to about a 150 km radius (BioCycle, 1992). Similar programs could work well elsewhere although

some type of subsidization (free material, transportation, or application) may be necessary initially.

Recommendations

Dairy cattle manure management systems are needed which economically utilize the material without negatively affecting the environment. Development of such systems requires funding for research, extension/education, and incentives for dairy farmers and land managers to implement the systems. **Specific areas of dairy cattle manure research requiring funding are:**

Development of improved methods for reducing N losses from the manure while in the barn or in storage.

Development of improved techniques for more uniformly and efficiently applying the manure to land.

Development of loading rate guidelines for amount of manure that can be applied without affecting air, surface water, or ground water quality.

Development of cropping systems that efficiently and economically use the manure while providing feed for cattle.

Development of improved technologies for alternative uses of the manure including energy production, refeeding, and composting to provide bedding or be used for soil amendments

Specific education/extension packages and incentive programs needing funding are:

Development of education/extension bulletins and computer packages which can be used by dairy farmers to assist in planning their manure utilization programs.

Development of education/extension programs to encourage non-dairy farmers to utilize locally available dairy cattle manure in place of or in addition to commercially prepared fertilizer.

Development of local, state-wide, or national incentive programs to assist both dairy and non-dairy farmers and land managers to utilize dairy cattle manure as a resource on their lands.

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V. Manure From Other Classes Of Livestock

Summary

In this section, manure production and utilization for sheep, goats, horses, veal calves, and mink are reported. While there are still other classes of livestock not discussed here, statistics for these are difficult to locate and their national impact is minor, as is that of several of the above species. The above five classes of livestock excrete about 90-100 thousand Mg (99-110 thousand tons) of N and 25 thousand Mg (28,000 tons) of P annually under confinement. About 60% of this is from horses and 30% from sheep. In comparison to other classes of livestock, on a national scale the problems created by these animals are small. However, such animals as horses and mink are often located in urban fringe areas where human population densities are greater than in more rural areas. Therefore, in such localities, odors and proper manure utilization may create conflicts. In general, manure produced by most of these species would be in solid form and would be handled similar to methods discussed for beef cattle.

A. Introduction

In addition to the livestock species discussed earlier in this report, several other types of livestock are often raised in confinement. These include species such as sheep, goats, horses, veal calves, and mink. A number of other species could be added to this list. While numbers of these livestock are often relatively low in comparison to those for the species discussed earlier, local problems in manure handling and utilization may still arise whenever these animals are concentrated. In many instances, these animals are produced in the fringes of urban areas, thereby adding to social problems associated with animal manure production and utilization.

B. Production

There are approximately 11 million sheep and 2.5 million horses in the United States, which contribute most of the manure N and P for this group of livestock (Table 1). However, there are few statistics available on many of the other livestock species. In Table 1 it is estimated that N and P excreted by a 45 kg (100 lb.) sheep is 10% of that excreted by

a 450 kg (1000 lb.) beef cow. Also it is estimated that 50% of the manure produced by horses is in confinement, and that manure production by a mink is similar to that for broilers. Very few goats are kept in confinement, so their recoverable manure production is negligible.

With these assumptions, total N and P recoverable in manure from horses would be 56 and 14 thousand Mg (62 and 15 thousand tons) per year, respectively. The next largest producer of manure in this group would be sheep. With 5 million head fed each year, manure N and P production in feedlots would be approximately 28 and 9 (31 and 10) thousand Mg (ton) per year, respectively. Manure N production by veal calves and mink would total only a few thousand Mg (tons) per year, while manure P production is in hundreds of tons. Thus for all classes of livestock listed in Table 1, recoverable manure N and P production would be only around 85 to 95 Mg (94-105 ton) N and around 25 Mg (28 ton) P. This is just a small percentage of the production by other classes of farm livestock, so total quantity is negligible on a national scale. However, as mentioned earlier, some of this livestock is often produced in urban fringes, where handling and utilization of manure is more of an issue. This is especially true for horses, whose numbers are increasing steadily. In the west-

Table 1. Sheep, goats, horses, veal calves, and mink in the United States. Numbers, confined numbers, and total N and P in manure from confined operations. (Fedkiw, 1992; Overcash, et al, 1983; U.S. Department of Agriculture, 1990).

Species	Head	Total confined	Manure produced		Confined annual production	
			per head			
			N	P	N	P
	Thousand		kg (lb) yr ⁻¹		1000 Mg ton yr ⁻¹	
Sheep	11000	5000	5.6 (12.4) ^a	1.6 (4.0) ^a	28 (31)	9 (10)
Goats	2000	-	-	-	-	-
Horses	25000	1250 ^b	46 (101)	11 (24)	56 (62)	14 (15)
Veal	350	350	1 (25) ^c	3 (8) ^c	0.3 (0.4)	0.1 (0.1)
Mink	4600	4600	.39 (.85) ^d	.09 (.19) ^d	2 (2)	.03 (.04)

^a Estimated 10% of value for beef

^b Estimated 50% confined

^c Estimated 20% value for beef

ern range regions, manure produced by horses in confined areas is generally small in quantity.

C. Management Systems

Much of the lamb fattening that occurs in the United States is in open pens, similar to beef feedlot operations. These feedlots are handled in much the same manner as beef feedlots, with once or twice per year cleaning. One difference is that lamb feeding is more seasonal, and feedlots may be idle part of the year. This may lead to more mineralization and a greater possibility for nitrification than for beef feedlots, but data are lacking. Lamb feeding occurs primarily in western states, such as California, Texas, Wyoming, and Oregon. Numbers are declining however, from 7.8 million in 1975 to 5.4 million in 1989.

Horses are generally kept on pasture or in stables or corrals or a combination of these two practices. While very few draft horses exist in the United States, saddle horses are found throughout the nation. In western states, these horses are used primarily in cattle ranches for working and caring for beef cattle. Few of these horses are kept in confinement for appreciable time periods. In the last several decades, numbers of pleasure riding horses have increased greatly, mostly on small acreages surrounding urban centers in each state. Many of these horses are kept in pens or stables for considerable time periods, requiring the periodic removal of manure. Often only a few horses are kept and there is sufficient pasture acreage in the operation to accommodate land utilization of manure. There are a limited number of instances (such as racing stables) where manure disposal from horses is a problem.

Mink are produced entirely in confinement, so eventually all manure produced must be utilized. There are approximately a million mink ranches in the United States (approximately the same as in 1975). While located across the northern half of the nation, states with the largest number of operations are Wisconsin, Minnesota, Oregon, Idaho, and Utah. While total quantity of manure produced on these ranches is small, these operations are

again often located near urban areas on limited land bases, so arrangements are often made with local farmers for manure utilization.

D. Agronomic And Environmental Effects

Agronomic and environmental effects of the manure produced by these classes of livestock do not differ greatly from those discussed earlier for other livestock classes. Almost all the manure produced is used for land application, although some horse manure is used for mushroom production. Because most of this manure is removed from confinement areas by scraping, utilization problems would be similar to those discussed for beef and consequences would be similar. No recent data exist on decomposition rate or nutrient availability of these manures, but presumably they would be somewhat similar to those for beef cattle.

E. Issues, Options, And Needs

In general, issues, options, and needs would be similar to those discussed for beef cattle. Because sources of these manures are produced near urban areas (horse and mink, in particular), odor problems may be more of an issue. However, opportunities for utilization of the manure for other than land application may also be greater.

Recommendations

As pleasure horse populations increase near urban areas, manure utilization problems will increase. Alternative uses of this manure need to be developed.

Odor control problems associated with animal production near urban areas will also require more research efforts.

Several of the recommendations on beef cattle manure utilization, particularly those as-

sociated with nutrient conservation and environmental control, would apply also to these classes of livestock.

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Agricultural Utilization of Industrial By-products

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I. Coal Combustion By-products

Summary

Total production of coal combustion by-products will reach nearly 154 million Mg (170 million tons) annually in the United States by the year 2000. Besides conventional combustion of coal for electric power which generates bottom and fly ashes, a number of newer by-products are generated by this industry. These newer by-products emanate from the need to reduce sulfur emissions. Typically, the desired desulfurization of the flue gases is accomplished by precipitating the sulfur oxides with calcium in the flues, or in the fire boxes with newer combustion technologies such as the fluidized bed systems. This diversity is further increased by differences in power plant design, sources and types of coal consumed, and, in the case of flue gas desulfurization, the types of reactive reagents utilized.

The lack of current utilization of most of these by-products, their diversity, and potentials for benefiting agriculture create the need for a database to facilitate agricultural utilization. The majority of the available data base information has been geared towards engineering properties of landfilled ash. An agricultural-oriented data base will facilitate the selection of those by-products exhibiting clearly definable benefits to the

soil/plant system and identify components such as boron, selenium, and heavy metals whose presence in soil should be maintained within certain limits.

Potential agricultural benefits from coal combustion by-products include alleviating soil trace elemental deficiencies, soil pH modification, and increasing needed calcium and sulfur, infiltration rates, depth of rooting, and drought tolerance. Flue gas desulfurization products and residues from fluidized bed combustion, which contain appreciable amounts of gypsum appear to have particularly high potentials for improving water use efficiency, product quality and productivity of soil-crop systems.

DRAFT

The existing literature on agricultural utilization of coal combustion by-products needs to be expanded to include data from long-term exposure of these materials in the soil environment. Potential sites for examination exist. Additionally, cooperative research should be initiated with the Department of Energy and private industry to evaluate the potential agricultural utilization of by-products emanating from new Clean Air technologies as they are developed. These studies should address not only new by-products but also incorporate innovative strategies for application and clear documentation of benefits derived.

Documentation of hazards involved and benefits derived, especially from field studies, will be required to reduce present regulatory barriers to agricultural utilization of coal combustion by-products. Current inexpensive disposal costs, usually on-site, discourage land application of coal combustion by-products. However, on-site disposal, may result in environmentally hazardous concentrations of certain elements and will preclude the use of the by-product materials for soil and crop improvement.

A. Overview

Fly ash produced from the burning of coal has become a generic term for all types of coal combustion by-products. Specifically, fly ash is that portion of the ash stream that has a sufficiently small size (0.001 to 0.1 mm) to be carried from the boiler in the flue gas. These particles are either mechanically captured or emitted via the stack.

Furnace residues from the combustion process, bottom ash and boiler slag, are common to all types of coal combustion. Both materials have a particle size within the 0.1 to 10 mm range. The amounts of boiler slag produced are projected to decrease due to newer boiler technologies. Currently, about 5% of the ash stream consists of boiler slag and about 25% bottom ash.

Total ash production varies considerably with the type of coal consumed as well as the source. Anthracite coal produces the highest ash content (about 30%) while bituminous coal can range from 6 to 12% ash (U.S. Environmental Protection Agency, 1988). Sub bituminous and lignite coals have a slightly wider range of ash contents, 5 to 19%. Current coal combustion produces, on average, about 10% ash.

There exist a number of other by-products which are dependent upon the type of combustion process and/or methodology used to reduce gaseous emissions, usually sulfur oxides. These include flue gas desulfurization by-products (FGD) (either wet or dry), fluidized bed combustion (FBC) by-products, and coal gasification ash. Coal gasification ash results from the conversion of coal into a synthetic gas or liquid fuels. The ash produced is similar to fly ash, therefore coal gasification ash will not be dealt with separately.

FGD by-products result from post combustion treatment (scrubbing) of the flue gas with an absorbent (usually lime (calcium oxide), limestone or dolomite) to reduce sulfur emissions. Such treatment may be performed under dry or wet conditions which affects the moisture status of the end-product. In the wet

method, flue gases pass through a slurry of absorbent in a contact chamber. In the dry method, a fine spray of absorbent is injected into the flue gas stream as it passes through the contact chamber. The water in the fine spray evaporates in the gas stream, leaving a dry powder end-product. The wet method tends to be more efficient (about 90%) than the dry method (about 70%) in the removal of sulfur from the flue gases. Thus dry scrubbing is usually performed when low sulfur coal is consumed. The major types of FGD systems currently in use are presented in Table 1-1. These types are classified as recovery or non-recovery systems based on the production of a salable (recovery) by-product such as sulfur, sulfuric acid or liquid sulfur dioxide. Such products are obtained from the Wellman-Lord process. This classification scheme (recovery and non-recovery) is not indicative of the potential for agricultural utilization. However, recovery and industrial utilization of these sulfur based by-products is limited. Therefore, the agricultural utilization of these sulfur-based by-products is warranted.

Table 1-1. Recovery and non-recovery types of FGD systems. Recovery systems produce industrially useful end products such as elemental sulfur.^a

Non-recovery Systems		Recovery Systems	
Wet	Dry	Wet	Dry
Direct lime (CaO)	Spray drying	Wellman-Lord	Alumina/Cu Sorbent
Direct limestone	Dry sorbent injection	Magnesium oxide	Activated C sorbent
Alkaline fly ash			
Dual-alkali			

^aSource: U. S. Environmental Protection Agency, 1988.

Of the FGD systems listed in Table 1-1, direct lime and direct limestone are the wet, non-recovery methods most used in the industry. The alkaline fly ash scrubber is used primarily with highly alkaline western coals for sulfur removal. The dual-alkali process uses a mixture of lime and sodium salts for sulfur removal.

Dry scrubbing methods such as spray-drying and dry sorbent injection have been under study by the industry since 1988.

A newer flue gas desulfurization system currently under study is the Pircon-Peck process. In this system, calcium phosphate (rock phosphate) is used as an absorbent rather than calcium carbonate (limestone). The by-product of this process contains both gypsum (calcium sulfate) and acidic phosphorus. The initial by-product is then ammoniated producing a mixture of gypsum and ammonium phosphate which provide four of the five nutrients needed in largest quantities by crops. However, if the Pircon-Peck process does prove to be economically feasible and gained the entire fertilizer market, it would use less than 15% of the sulfur by-product expected from coal combustion in 2000 AD.

The simultaneous combustion of coal and an absorbent (usually limestone or dolomite) in fluidized bed combustion results in end products very different than combustion of coal per se. The calcium reacts in the furnace as an absorber of sulfur, thereby reducing flue emissions of sulfur and producing large amounts of a dry by-product. The bottom and fly ashes contain substantially higher concentrations of calcium including calcium sulfate and some calcium oxide compared to conventional plants and display an alkaline pH (usually about 12).

A similar new technology is the limestone injection multistage burner (LIMB). A calcium-based sorbent is injected into the burner to achieve sulfur removal as with FBC. The LIMB technology is used to retrofit existing boilers. The dry by-product obtained is easier to handle than traditional wet scrubber wastes.

A diverse range of coal combustion by-products exists ranging from those produced in conventional facilities to an ever growing list of flue gas desulfurization by-products plus newer combustion technologies such as fluidized bed combustion. The potential exists to utilize many of these by-products in agriculture.

B. Amounts Produced

Fly and Bottom Ash

The utilization of coal to produce power consumes large quantities of coal annually. For example, coal consumption in Georgia alone was 24.5 million Mg annually resulting in 2.0 million Mg of fly ash and 0.5 million Mg of bottom ash (McIntosh, 1992). Therefore, fly and bottom ashes are produced at about 10% of the coal consumed. These figures do not reflect amounts due to new Clean Air technologies such as flue gas desulfurization scrubber by-products. Installation of scrubbers at selected plants in Georgia alone, will produce an additional 1 million Mg of FGD materials annually.

Nationally, about 63.6 million Mg of fly and bottom ash were produced in 1984 (U.S. Environmental Protection Agency, 1988) (Table 1-2). Projected future use of coal will increase this figure to about 109 million Mg annually by the year 2000 (U.S. Environmental Protection Agency, 1988). These figures do not include the amounts of FGD and FBC material generated.

Flue Gas Desulfurization (FGD) by-products

Flue gas desulfurization systems for the scrubbing of flue gases are classified as either recovery or non-recovery technologies (see Table 1-1). Recovery methods of flue gas desulfurization produce industrially recyclable by-products such as elemental sulfur and liquid sulfur dioxide. Non-recovery techniques result in by-products for which there is no current use and disposal involves added cost. Approximately 95% of current FGD

Table 1-2. Past, present and projected amounts of by-products produced by the coal combustion industry.

By-product	Past	Present	Projected
Type	Production (1984)	Production (1991)	Production (2000)
-----million Mg-----			
Ash			
Total ^a	62.6	64.2	109
Fly	—	46.6	78.6
Bottom	—	12.8	26.3
FGD	14.5	16.3	45.4

^a includes boiler slag.

Sources: U.S. Environmental Protection Agency, 1988;
American Coal Ash Association. Washington, D.C.

technologies produce non-recovery by-products (U.S. Environmental Protection Agency, 1988). Both technologies are further classified as wet or dry systems to indicate the moisture status of the end-product. From an agricultural utilization viewpoint, the end-products produced are quite variable and will require different strategies for their effective use.

FGD production in 1985 was about 14.5 million Mg which includes all types of by-products (U.S. Environmental Protection Agency, 1988). It is estimated that this figure will increase to about 45.4 million Mg annually by the year 2000.

Fluidized Bed Combustion By-products

Because both FBC and other calcium-based dry by-product technologies such as LIMB are just beginning to come on-line in significant capacity annual production figures for these types of by-products are not available. It has been estimated that a 1000 megawatt FBC plant would generate about 1,800 Mg of dry waste per day or about 0.64 million

Mg annually (Ruth, 1975). About 110 FBC plants are currently in operation with an additional 13 plants under construction (J. Solem, personal communication). Residue production is over 18.2 million Mg per year. These gypsiferous materials may be among the most suited for agricultural utilization.

C. Chemical Composition Of Ash

Conventional Fly Ash and Bottom Ash.

The chemical constituents of ash can vary greatly depending upon the coal type and source. Major constituents include aluminum, calcium, iron, magnesium, potassium, silicon, sodium, and titanium. Of these eight primary constituents which make up 95% of the ash, five are agriculturally important plant nutrients. The concentrations of these primary constituents and their agricultural importance are listed in Table 1-3.

Trace element concentrations in ash are also variable and can have an impact on the

Table 1-3. Concentration ranges for major elemental constituents of ash.^a

Element	Fly ash	Bottom ash
-----%		
-----Essential Plant Nutrients-----		
Calcium	0.5 - 17.7	0.8 - 5.1
Iron	0.8 - 28.9	2.7 - 20.3
Magnesium	0.5 - 6.1	0.4 - 3.2
Potassium	0.2 - 3.5	0.7 - 1.6
Silicon	19.6 - 27.1	18.0 - 27.3
-----Other Elements-----		
Aluminum	1.1 - 14.4	8.8 - 13.5
Sodium	0.1 - 2.0	0.2 - 1.3
Titanium	<0.1 - 1.6	0.3 - 0.7

^aSource: Utility solid waste activities group, 1982.

potential agricultural utilization of these materials. Ranges of trace element contents present in a broad sample of ash and types of coal are presented in Table 1-4 and agriculturally important trace elements are identified.

Although the values in Table 1-4 are average concentrations, significant variations in trace element contents are shown for various coal sources (eastern, midwestern, and west-

Table 1-4. Trace element concentration ranges in ash averaged over all ash and coal types ^a

Element	Overall Range (mg kg ⁻¹)		
-----Essential Plant and Animal Nutrients-----			
Boron	10	-	1300
Copper	3.7	-	349
Manganese	56.7	-	767
Molybdenum	0.84	-	100
Nickel	.8	-	258
Selenium	0.08	-	19
Zinc	4.0	-	2300
-----Other Elements-----			
Arsenic	0.50	-	279
Barium	52	-	5790
Cadmium	0.10	-	18
Chromium	3.4	-	437
Cobalt	4.9	-	79
Fluorine	0.4	-	320
Lead	0.4	-	252
Mercury	0.005	-	4.2
Silver	0.04	-	8
Strontium	30	-	3855
Thallium	0.10	-	42
Vanadium	11.9	-	570

^aSource: Tetra Tech Inc., 1983.

ern). Midwestern coal ash is usually highest in cadmium, zinc, and lead while barium and strontium are highest in western coal. Selenium tends to be higher in eastern and midwestern coals.

Coal cleaning, prior to combustion, can significantly reduce elemental concentrations of sulfur, selenium, and other trace elements. The cleaning is performed using physical (usually density differences separating out pyretic-sulfur), chemical or biological precombustion

cleaning. The latter two methods are newer and not currently used extensively. Coal cleaning can also have a significant impact on the amount of ash generated. In Virginia, raw coal produced an average 9.7% ash while cleaned coal produced 5.7% ash (Randolph et al., 1990). Precombustion cleaning of coal is one of several categories of clean coal technology currently being funded and developed under the Department of Energy (U.S. Department of Energy, 1991).

Elemental concentrations also vary with the particular portion of the ash stream sampled. Fly ash contains significantly higher quantities of arsenic, copper, and selenium than bottom ash. Distribution of elements in the ash stream is highly dependent on boiler temperature and therefore can vary greatly. Some components such as elemental sulfur and mercury are essentially completely volatilized, thereby reducing their concentrations in bottom ash in conventional coal burning plants.

Currently, fly ash types are classified on the basis of major components. Class C fly ashes contain less than 70% but greater than 50% of silica, alumina, and iron oxides and are usually denoted as high-lime, western ashes. If the content of silica, alumina, and iron oxides exceeds 70%, ashes are classified as Class F and are usually generated from eastern coals (Environmental Management Services, 1992). A modification of this fly ash classification system has been proposed. This modification is based on a more detailed chemical composition (Roy et. al., 1981). The three basic groupings proposed are silica (silicon-aluminum-titanium oxides), calcic (calcium-magnesium-potassium-sodium oxides), and ferric (iron-manganese-sulfur-phosphorus oxides). Use of such a classification system would be an initial step in helping to identify potentially useful by-products. Expansion of the list to include agriculturally related parameters such as plant nutrient availability indices and potential elemental phytotoxicity indices, would facilitate communication between different research groups and development of cost effective and environmentally beneficial uses of these ashes.

Flue Gas Desulfurization (FGD) By-products

Independent of the type of process used (see Table 1-1) to scrub the flue gas, all FGD products include spent reagent in combination with sulfites or sulfates plus un-reacted reagent. Additionally, the FGD material may contain water (in wet processes) and coprecipitated fly ash. The quantity of reagent used is usually proportional to the sulfur content of the coal burned but is also a function of the percent SO_x recovery desired as well as system operating parameters.

Generally, wet scrubbers produce slightly smaller particle sized material (0.001-0.05 mm) than dry scrubbers (0.002-0.074 mm). Wet scrubber sludge can vary from 16 to 43% moisture.

The chemical composition of FGD sludges will by necessity vary depending upon the process employed as well as quantity of reagent used, amount of fly ash present, the sulfur content of the burned coal and whether or not forced oxidation is used in the treatment process. The degree of forced oxidation used in the process which produces the FGD sludges has a significant impact on the potential use of the material in agriculture since increased oxidation increases the amount of sulfates compared to the amount of sulfites present in the end-product. This range is illustrated in Table 1-5.

Table 1-5. Effect of FGD process and coal source (eastern and western) on the chemical components of the end-products produced. Values are percent of total FGD sludges^a

Component	Process				
	Direct lime (CaO)		Direct limestone CaCO_3		Alkaline fly ash (NaOH)
	East	West	East	West	West
	-----%				
CaSO_4	15-19	17-95	5-23	85	20
$\text{CaSO}_3 \cdot 1/2 \text{H}_2\text{O}$	13-69	2-11	17-50	8	15
Ca-sulfite	1-22	0-3	15-74	6	—
Fly ash	16-60	3-59	1-45	3	65

^aSource: U.S. Environmental Protection Agency, 1988.

Dual-alkali and spray drying systems that utilize a sodium absorbent will produce FGD sludges containing sodium sulfate (oxidized) or sodium sulfite (reduced). Since sodium deteriorates soil structure these sodium containing FGD sludges will probably not be used in agriculture.

A comparison of the primary chemical components of a direct lime (calcium oxide) FGD versus a dual-alkali FGD is shown in Table 1-6. The differences in calcium and sodium contents of the two FGD scrubber products highlights the need for an awareness of the process used in relation to agricultural utilization. The ratio of sulfate to sulfite is also important in relation to the solubility of the end-product. Sulfites are lower in solubility. Installation of an oxidizing step in the FGD process, although an additional expense, aids not only in increasing the solubility of the end product but also increases the potential for agricultural utilization due to higher gypsum concentration. On the other hand there is preliminary evidence that sulfite sludges applied to soils several weeks prior to planting crops are oxidized to sulfates before the crops begin to grow. Consequently there is a lack of an initial negative effect on plant growth that is observed when they are applied at planting time. Investigations on the behavior of sulfite materials in the soil/plant system are currently being performed at the Beckley West Virginia, Agr. Res. Ser. Laboratory.

Table 1-6. Primary chemical components of FGD processes that use a calcium-based absorbent (direct lime) or a sodium-based sorbent (dual-alkali).^a Both by-products were obtained by burning eastern coal. Concentrations are in mg kg^{-1}

Component	Direct Lime	Dual-alkali
pH	8 - 9.4	12.1
Potassium	11-28	320-380
Sodium	36-137	53,600-55,300
Calcium	660-2520	7-12
Magnesium	24-420	0.1
Sulfate	800-4500	80,000-84,000
Sulfite	0.9-2.7	—

^aSource: U.S. Environmental Protection Agency, 1988.

The pronounced difference in trace element concentrations in the solid and liquid component of wet scrubber sludges is shown in Table 1-7. With the exception of boron, most trace elements remain associated with the solid FGD material. The percent of soluble boron present in these materials may be of significance in the soil/plant system. Plants are sensitive to boron concentrations. High available boron levels may induce a toxicity. However, where boron is deficient, additions of boron-bearing sludges may be beneficial. Such potentials for benefits from careful management are explored later in this report (see Trace Element Dilemma Section G).

Fluidized Bed Combustion

Table 1-7. Trace element concentration ranges in wet FGD solids and liquors.^a Values are in mg kg⁻¹.

Element	Solids	Liquors
-----Essential Plant and Animal Nutrients-----		
	mg kg ⁻¹	
Boron	42-530	2-76
Copper	6-340	<0.01-0.5
Selenium	2-60	<0.01-1.9
-----Other Elements-----		
Arsenic	0.8-52	<0.01-0.1
Cadmium	0.1-25	<0.01-0.1
Chromium	1.6-180	<0.01-0.3
Fluoride	266-1017	0.2-63
Mercury	0.01-6	<0.01-0.1
Lead	0.2-290	<0.01-0.5

^aSource: U.S. Environmental Protection Agency, 1988.

By-products

Fluidized bed combustion (FBC) by-products also vary in elemental composition. Range of elemental concentrations from a representative FBC plant utilizing eastern coals are presented in Table 1-8. The large amounts of calcium present in the by-product are primarily in the form of gypsum and un-reacted sorbent, calcium oxide. A typical analysis for a spent bed material has an aqueous pH of about 12 containing (in % dry wt) 52 CaSO₄,

33 CaO, 0.6 CaSO₃, 0.8 MgO, 0.3 NaCl, 0.02 P₂O₅, 4.5 R₂O₃ (primarily iron and aluminum oxides), and 7 SiO₂ (Korcak, 1988). This combination of calcium-based by-products is an especially useful material being high in both acid neutralizers (calcium oxide) and the relatively soluble and mobile calcium and sulfate in the gypsum. Generally, trace element concentrations follow those of other coal combustion by-products and these levels will vary depending primarily upon the constituents of the coal and sorbent utilized in the combustion process.

Table 1-8. Major and trace element concentration ranges in fluidized bed combustion (FBC) by-products compared to ranges normally found in soils ^a.

Element	FBC	Soil
Calcium (%)	24-46	0.7-50
Aluminum (%)	0.4-2	4-30
Sulfur (%)	7.2-14	0.01-2
Iron (%)	0.08-1.6	0.7-55
Magnesium (%)	0.5-1.2	0.06-0.6
Potassium (%)	0.05-0.8	0.04-3
phosphorus (mg kg ⁻¹)	380-500	50-2000
Manganese (mg kg ⁻¹)	210-685	200-3000
Boron (mg kg ⁻¹)	95-170	2-100
Molybdenum (mg kg ⁻¹)	0.12-0.28	0.2-5
Copper (mg kg ⁻¹)	12-19	2-100
Zinc (mg kg ⁻¹)	29-105	10-300
Nickel (mg kg ⁻¹)	13-29	5-500
Lead (mg kg ⁻¹)	1.5-7.5	2-200
Cadmium (mg kg ⁻¹)	0.5	0.01-0.7
Chromium (mg kg ⁻¹)	9-23	5-1000
Selenium (mg kg ⁻¹)	0.16-0.58	0.01-2

^aSources: Stout, et al., 1988. and Page, et al., 1979.

D. Organic Composition Of Coal Combustion By-products

There are many incompletely oxidized organic compounds in fly ash. Roy, et al. (1981) lists a number of carcinogens and/or mutagens in ash per se. It is difficult to track

organics in flue gases exiting the power plants due to climatic and atmospheric effects on composition of air entering the burners. These changes which occur in the stack prior to capture may not accurately reflect toxicity estimates.

Organics have received little attention in studies on agricultural utilization of coal combustion by-products. Research on the transformation and fate of organics in the soil/plant system is difficult. Additionally, stock-piled, weathered ash may present a different organic composition compared to fresh materials.

Based on past studies in related areas it appears that the primary hazards to human health would be via direct inhalation by operators applying these materials rather than via plant uptake and food consumption. However, the potential hazards for contamination by organics needs to be documented.

E. Mineralogy Of Coal Combustion By- Products

There is considerable information on the mineralogy of coal combustion by-products. Most of this work has been performed on fly ash (see for example Roy et al., 1981) and has examined particulates. Importantly, this work has shown a strong association between fly ash particle size and trace element concentration (Davidson, et al., 1974). Concentrations of selenium, cadmium, arsenic, lead, nickel, chromium and tin increased with decreasing particle size. Similarly, Phung, et al., (1979) found enhanced levels of boron, chromium, molybdenum, nickel, arsenic, and selenium associated with fly ash particle sizes $< 53 \mu\text{m}$. This association may prove beneficial for the further utilization of fly ash in agriculture since mechanical removal and separation of small fly ash particles at the plant site could reduce the risk of trace element contamination. However, this additional operation may not be economically feasible.

In summary, many trace elements, particularly those to which plants and animals are highly sensitive (i.e. boron, selenium, and mo-

lybdenum), tend to be associated with the finer particle-sized fly ash. Therefore these finer materials should be carefully analyzed and applied on a prescription basis according to needs. Utilization of bottom ash and FGD materials not mixed with fly ash can probably be in larger amounts. The same would hold true for bottom ashes from FBC and newer technologies such as LIMB. However, these indications need further documentation on the full range of by-products considered for agricultural use.

Only recently have studies been initiated on the mineralogy of coal combustion by-products applied to agricultural soils. The short- and long-term fate of mineral forms in the soil-system needs to be examined.

The pozzolanic nature of FBC materials was used to benefit apple orchards (Korcak, 1988). Rates of spent bed material up to 112 Mg ha^{-1} ($50 \text{ tons acre}^{-1}$) were applied as a within row cap in an established apple orchard. The surface applied material formed a porous cement which prevented weed growth for up to four years after application. Over six years, cumulative yields were increased in three of four cultivar-rootstock combinations. Foliar magnesium levels decreased with time from high FBC material application, reflecting the greatly increased soil calcium status and the decrease in magnesium levels in the surface soil horizons caused by leaching.

These apple plots were re-examined twelve years after the initial application and five years after the plots were plowed (Korcak, unpublished data). X-ray diffraction patterns of remnant cemented pieces of the applied spent bed ash showed that most of the original calcium oxide had converted to calcium carbonate (calcite). Besides calcite the other dominant mineral present was quartz. Secondary minerals present were gypsum and ettringite (Figure 1-1). The formation of calcium carbonate with time is expected and leads to the maintenance of a relatively high pH (not exceeding pH 8.3, which is the equilibrium pH for calcium carbonate). Surface pH values from these plots after twelve years were about 7.6. However, the mineral ettringite is unstable at pH levels less than 10. Therefore, the presence of even trace et-

tringite indicates the existence of micro-environments with a pH of at least 10 within the soil matrix. This further indicates that some un-reacted calcium oxide is still present albeit the amount is small. Therefore, application of these materials at relatively high rates, 112 Mg ha^{-1} , can have long-lasting effects on the soil environment and soil mineralogy.

waste regulations. These regulations vary greatly from state to state ranging from very stringent to total exemption from regulation for on-site disposal. Approximately 80% of coal combustion by-products are treated, stored, and/or disposed by means of land management with the remaining 20% recycled (U.S. Environmental Protection Agency,

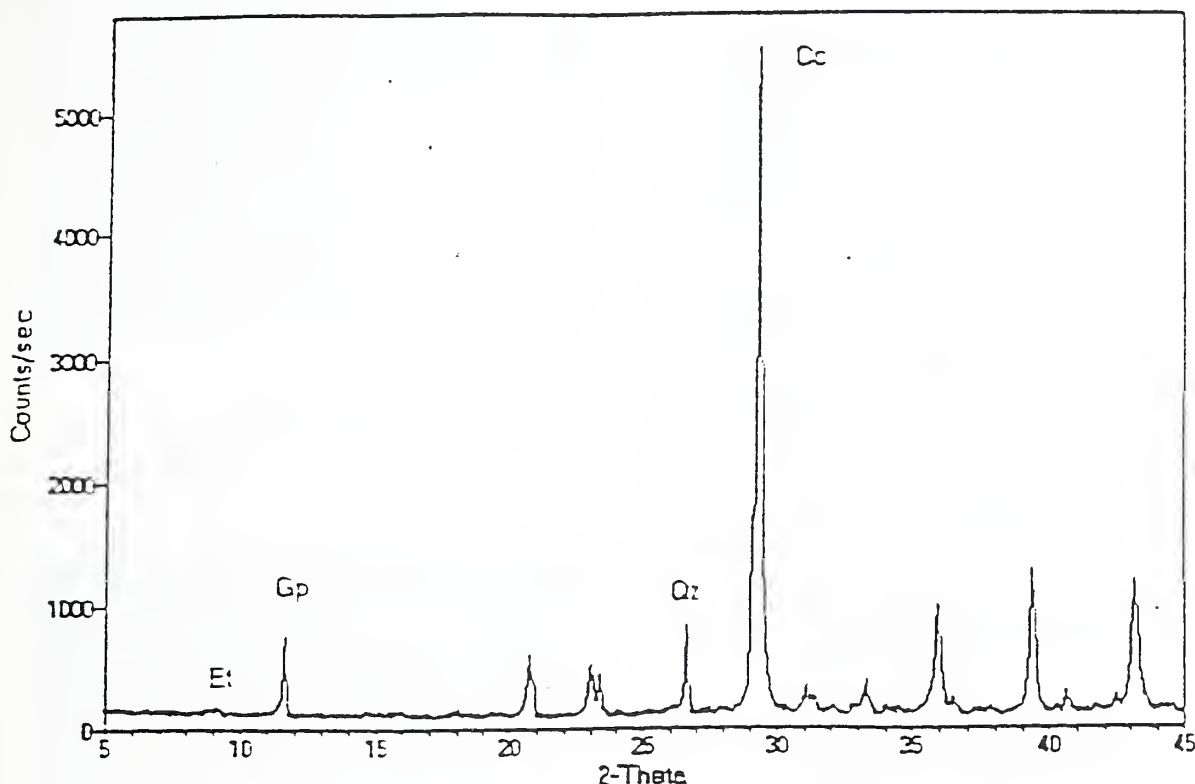


Figure 1-1 X-ray diffraction pattern from a 12 year-old piece of FBC spent bed material that was surface applied and later soil incorporated. Cc=calcium carbonate, Qz=quartz, Gp=gypsum, Et=ettringite.

Studies are needed on the mineralogy of coal combustion by-products not only for fresh materials but also for weathered by-products and materials that have been exposed to the soil environment for various periods of time. Such studies will provide information on the eventual fate of trace elements included in these minerals as well as on changes in soil chemistry and soil mineralogy.

F. Current Non-agricultural Disposition

Coal combustion by-products are generally regulated by individual states under solid

1988). Land management techniques include surface impoundments, landfills, and placement in mines and quarries. Impoundments and landfills are the two most widely used land management methods, with about 77% of facilities using one of these methods.

The overall cost incurred in the management of coal combustion wastes ranged from \$2.20 to \$34.14 per Mg in 1988 (U.S. Environmental Protection Agency, 1988). This cost is generally rising rapidly as are costs for landfill disposal of other wastes. This range in cost depends upon the type and size of facility and the characteristics of the waste generated. Generally, fly ash is more costly to manage than bottom ash or FGD wastes. Therefore en-

vironmentally sound recovery/recycling of coal combustion by-products can have a significant effect on the costs incurred by the industry in dealing with waste streams.

Recovery and/or recycling of coal combustion by-products varies with the particular end-product. Coal ash utilization increased from 18% for the 1970-1980 period to 27% in 1985 (U.S. Environmental Protection Agency, 1988). However, less than one percent of all FGD products were recovered and utilized. This situation may change as industry develops more efficient recovery/utilization processes. A summary of recovery/utilization processes is shown in Table 1-9. Although about 20% of ash products are utilized or recycled the current expectation is that this percentage will not increase in the foreseeable future.

Conventional Bottom And Fly Ash

Fly ash and bottom ash may exhibit pozzolanic properties whereby the dried material forms a hard cement-like material. Carefully selected ashes are used as pozzolans in the manufacture of cement. However, high concentrations of sulfates or nitrates reduces desirability of these pozzolans for this purpose. As will be noted later, the pozzolanic nature of some coal combustion by-product materials can be beneficial in certain surface application techniques in agriculture.

Flue Gas Desulfurization By-products

Recovery/recycling of FGD by-products is limited. Many of the construction related uses of fly ash are not appropriate for FGD materials since they generally possess standard pozzolanic properties. Some FGD processes such as dry scrubbing result in gypsum which can be used as a replacement for mined gypsum in wallboard production. However, this use could account for only a few percent of the FGD by-products expected in response to the Clean Air Act. These FGD by-products are currently considered to be of lower quality for this purpose than mined gypsum. Newer

technologies are under study to increase the production of sulfur-related chemicals from FGD sludges.

Fluidized Bed Combustion By-products

Due to the relatively recent increase in the number of FBC plants, data is lacking on recovery/recycling uses for FBC by-products (see Table 1-9). Some of the advantages for utilization of these materials for construction purposes include its dry nature which reduces hauling costs, and some degree of pozzolanic properties. However, the initial changes in volume of the minerals as they absorb large amounts of water and generate heat make them difficult to use for engineering purposes. The same would hold true for similar by-products from the limestone injection multistage burner (LIMB) FGD materials.

Table 1-9. Current non-agricultural recovery/utilization techniques for different coal combustion by-products.

By-product	Recovery Use	% Used
Bottom ash	Blasting grit, road and construction fill, roofing granules	33
Fly ash	Concrete admixture (pozzolan), cement additives, grouting, road and construction fill, stabilization of hazardous wastes, clay liner additive, magnetite production, asphalt amendment	17
FGD products	Sulfuric acid, sulfur, other sulfur products (currently limited in scope), gypsum	< 1
FBC products	Cementation of hazardous wastes, cement additive	?

Land Utilization

Coal combustion by-products have been used as an amendment for disturbed lands. Work has been performed on mined land reclamation and renovation of coal refuse piles around the United States (Jastrow et al., 1981; Fail, 1987; Taylor and Schuman, 1988; Stehouwer and Sutton, 1992). A recent review

has been made on the use of fly ash in mined land reclamation (Haering and Daniels, 1991). The extremely acidic nature of these lands (i.e. resulting from oxidation of sulfur and sulfites) often requires basic material additions to bring pH into the range where plants grow and keep trace element concentrations at desired concentrations in soil solution. Consequently the use of power plant by-products which are generally alkaline can assist in moderating pH to the desired levels to reduce trace element availability. There have been and there are ongoing projects looking at the co-utilization of coal combustion by-products and organic amendments such as sewage sludge in disturbed land reclamation. The addition of sewage sludge provides a nitrogen source for plant establishment and growth. As with coal combustion materials, the addition of sewage sludge requires the maintenance of a suitable pH to keep trace elements in the desired concentration ranges.

The utilization of fly ash and other coal combustion by-products with or without the addition of an organic material may allow re-vegetation without application of a topsoil cap. Addition of a topsoil cap is generally the major expense in reclamation of disturbed lands. Successful re-vegetation with trees on abandoned ash basins has been reported without the need for a top soil capping (Carlson and Adriano, 1991).

G. Agricultural Utilization Of Coal Combustion By-products

Overview

To justify utilization, any amendment to the soil/plant system must exhibit a clearly defined benefit to the environment (soil, water and/or air) or to the quality and for the quality of the crops to be produced. These benefits must exceed the costs and hazards whether one is applying a fertilizer, organic mulch, irrigation or an industrial by-product. Potential benefits and hazards stemming from the agricultural utilization of various coal combustion by-product materials are noted below fol-

lowed by a review of past and ongoing research performed and results obtained on the effects of coal combustion by-products on soil chemical, physical, and microbiological parameters as well as plant growth. This discussion is limited to studies dealing with the utilization of coal combustion by-products on agricultural land.

Potential Benefits

There are a number of potential benefits of applying coal combustion by-products to agricultural soils. These can be classified as either chemical or physical. Chemical benefits can be derived by supplying essential plant nutrients for crop production (e.g., supplying boron to a boron deficient soil) or by modifying the soil to create a more favorable medium for plant growth (e.g., modifying the soil pH and decreasing aluminum toxicity).

Physical benefits include increased water infiltration and aggregation of the soil which under certain conditions can be attained through gypsum applications. As noted, a major constituent of most FGD by-products and residues from FBC and LIMB is gypsum. Since gypsum-containing coal combustion by-product materials are the most likely candidates for agricultural utilization, a brief discussion of the benefits of applied gypsum is included in Appendix A.

Definition of potential benefits from coal combustion by-product utilization may be complex in that separation of a chemical or a physical benefit is not feasible. As an example, application of high-gypsum FGD material may increase water availability and crop yield as a result of reduction of subsoil chemical restrictions on rooting depth but also because of benefit in increasing water infiltration into the surface soil, which is considered a physical benefit.

In addition to providing a clearly definable benefit, the application of coal combustion by-products must not create a hazardous condition in the soil, ground water, plants, or the food chain. Prevention of adverse conditions will, in most cases, be attainable by selecting appropriate by-products and utilizing

them at appropriate rates. A distinction must be made between utilization and disposal application rates.

Potential Hazards

The primary potential hazards from agricultural utilization of coal combustion by-products are excessive trace element loadings resulting in increased food chain metals, high soluble salt loadings which may reduce initial plant growth, sodicity resulting from high sodium-containing by-products which reduce water infiltration; negative effect of sulfites on crop growth and leaching of toxic substances into the ground water. Although the potential for these hazards exists, all can be controlled in agricultural situations by judicious application of selected coal combustion by-products. For instance, careful limitation of the use of fly ashes known to be enriched with trace elements can control the loading of these elements to the soil and keep their concentrations in the beneficial or benign ranges in terms of leaching and/or plant uptake. Many coal combustion by-product materials are highly alkaline and can reduce plant establishment due to an initial elevation of soluble salts. One method to alleviate this potential hazard is to surface apply coal combustion by-products and then plow to incorporate the material essentially as a layer below the germinating seeds (R. B. Clark, personal communication). Sulfite by-products applied at planting have reduced rates of crop growth, but oxidation to sulfate may be sufficiently rapid in some soils that application of sulfite-bearing by-products a few months before planting will avoid harmful effects.

Induction of plant nutrient deficiencies of phosphorus and magnesium are secondary potential problems in certain situations. Application of flue gas desulfurization by-products or fluidized bed combustion materials originating from facilities using a calcium-based sorbent can create an imbalance in the soil calcium to magnesium ratio. This may result in an induced magnesium deficiency. Fortunately, magnesium deficiency is usually easily corrected by the soil application of magnesium sulfate (Epsom salts). Therefore, care must be taken to monitor the calcium to mag-

nesium ratio of the material applied and in the soil at the application site.

The high level of calcium and/or iron and aluminum in some coal combustion by-products can result in the formation of insoluble complexes with phosphorus. These complexes reduce the availability of phosphorus to plants which may result in an induced phosphorus deficiency.

However, there may be situations where the formation of these insoluble phosphorus complexes is desirable. The potential co-utilization of fluidized bed combustion (FBC) ash and poultry manure is currently being examined (Korcak, unpublished data). One of the limitations on land utilization of poultry manure in intensive poultry producing states is the potential for phosphorus pollution of surface and sub surface water supplies. Co-utilization of the high calcium FBC material with poultry litter may form insoluble calcium-phosphorus complexes which will reduce potential phosphorus pollution problems.

Physical-chemical Interactions Of Coal Combustion By-products In The Soil/plant System

The trace element dilemma Most reports on the utilization of coal combustion by-products in agriculture conclude that the most serious potential hazards stem from boron, selenium, arsenic, and molybdenum accumulation in soils and plants. However, coal combustion by-products can act as a supplementary source of calcium, sulfur, boron, molybdenum, selenium, and other trace elements when soil contents are deficient for adequate plant growth. Rates of ash application which achieve sufficient and excessive concentrations of these trace elements are often site-specific and therefore need to be more thoroughly examined before coal combustion by-products are utilized on a large-scale.

Selenium is not an essential element for higher plant growth, although it has been shown to be a required element for some lower plant species. However, selenium is an

essential element for animal growth. The problem is accentuated since selenium in animal nutrition is needed only in very low concentrations; slightly higher concentrations cause selenium toxicity. Recommended food and feed concentrations to provide adequate animal selenium range from 0.1 to 1 mg kg⁻¹. Food and feed selenium concentrations above 5mg kg⁻¹ can cause animal selenium toxicity (Mengel and Kirby, 1987). Therefore, the elevation of selenium in plants above 5mg kg⁻¹ is detrimental, if these plants make up 100% of the animal ration. On the other hand, low selenium is also detrimental. It is estimated that one-third of the forage and grain crops in the U. S. are below optimal in selenium (Mengel and Kirkby, 1987). Welch et al. (1991) provide an excellent discussion of micro nutrient needs and availability in soils and maps showing areas where selenium, copper, and molybdenum are high in crops, areas where they are sufficient and others where additions of these elements are needed to optimize crop production and animal health.

A clearly defined benefit of coal combustion by-product use in agriculture would be to correct sub optimal concentrations of plant selenium. Similarly, molybdenum, copper, and boron deficiencies may also be ameliorated.

Trace element deficiencies of boron, molybdenum, copper, and zinc have been corrected by the application of coal combustion by-products. A number of reviews of fly ash utilization in agriculture have summarized the use of coal combustion by-products in correcting trace element deficiencies (Page, et al., 1979; Adriano, et al., 1980; Aitken, et al., 1984; El-Mogazi, et al., 1988; Brieger, et al., 1992; Environmental Management Services, 1992). The application of by-products should be based on crop needs and current soil levels of the particular nutrient. An example of the calculation of pounds of nutrient per ton of fly ash from either weight percent oxide or mg kg⁻¹ content in the ash is presented in Table 1-10.

In some ashes boron and selenium appear to have sufficiently high concentrations to warrant limitation of amounts of those ashes used on agricultural crops (e.g. Ransom and Dowdy, 1987). Additional studies are needed to define mineralogy, solubilities,

uptake rates, and plant responses needed to calculate optimum application rates at which such ashes can and should be used on different soils.

Table 1-10. Converting the weight percent oxide content to cation content. This example is for a sample bottom ash^a.

Compound	%oxide by Wt	Conversion Factor	%	Elements kg Mg ⁻¹	Element
Al ₂ O ₃	13.40	0.53	7.09	70.8	Al
CaO	6.80	0.71	4.86	48.5	Ca
K ₂ O	2.10	0.83	1.74	17.4	K
MgO	0.74	0.60	0.45	4.5	Mg
SiO ₂	60.10	0.47	28.29	280.3	Si
TiO ₂	2.50	0.60	1.50	15.0	Ti
Fe ₂ O ₃	14.40	0.70	10.07	100.5	Fe
	mg kg ⁻¹				
Boron	15.00	0.002	0.00	0.015	B
Nitrogen	8.00	0.002	0.00	0.008	N
Sulfur	32.00	0.002	0.00	0.032	S

^a From: Bryant and Lacewell, 1992

Soluble Salts

Besides trace elements, the other major concern with the agricultural utilization of coal combustion by-products is the high soluble salt content of many materials. At high application rates, salt injury can occur to germinating seeds or established plants. The problem of high soluble salts can be alleviated in a number of ways. As noted earlier, surface application of coal combustion by-products followed by plowing allows seeds to germinate without contacting the high salt zone. A similar technique was used by Jacobs et al. (1991) where ash was banded into the soil at a 45° angle to the surface. These two methods isolate the applied material from initial root contact. Most application methods homogenize the applied ash into the surface soil and maximize seed contact. Additionally, the timing of application can have a significant impact on avoiding initial soluble salt-related problems.

Another method to avoid soluble salt problems would be the use of weathered or

stock piled material from which a substantial portion of the soluble salts has been removed by percolation and some of the oxides and hydroxides have been stabilized by carbonation. Weathered versus fresh fly ash was compared on field trials with corn (Martens and Beahm, 1976). Weathered ash could be used at rates up to 131 Mg ha^{-1} while salt-related problems occurred at 87.2 Mg ha^{-1} using fresh ash. Also of interest was a decrease in the incidence of boron toxicity with weathered ash. As previously noted (see Table 1-7) a relatively high percentage of the boron in ash is soluble. Therefore, lower amounts of water soluble boron will be applied to soils when weathered ash is utilized.

The use of weathered materials also decreases the dust hazard associated with applying fresh dry coal combustion by-products because bonding and recrystallization during moist weathering reduces the amount of small size particles.

A third method to reduce the potential for soluble salt problems has been the successful use of FBC residues as a soil 'cap' wherein a thick (5 cm) layer of FBC residue is surface applied and not plowed or mixed with the soil (Korcak, 1988). This method, used with horticultural crops, provides either sufficient soil mass for the roots to avoid contact with the initial flush of soluble salt or reduces this initial flush to levels that can be tolerated by crops. The 'cap' of coal combustion by-product remains porous, allowing water to infiltrate. An associated benefit of the 'cap' method for utilization is that the 'cap' acts as a one-way valve: it allows water to infiltrate but decreases evaporation from the surface.

Effect on soil chemical properties Owing to the alkaline nature of many coal combustion by-products, a number of studies have examined their effect on modifying soil chemistry, primarily pH. The basic property of coal combustion by-products measured to quantify the effect on soil pH is the calcium carbonate equivalence of the materials. The neutralizing effect of pure calcium carbonate is 100% and that of coal combustion by-products usually ranges from 20 to 60%. Therefore, if a coal combustion by-product has a calcium carbonate equivalence of 50%, twice as much coal

combustion by-product as calcium carbonate is needed to neutralize the same amount of soil acidity.

Successful modification of soil pH has been demonstrated with a wide range of coal combustion by-products. Agricultural applications in most situations will probably be based on soil pH modification.

FBC residues and oxidized FGD materials also contain significant amount of gypsum and/or its anhydride. The effect of gypsum on soil properties is discussed in Appendix A. The potential benefits derived from gypsum applications in certain soils make those coal combustion by-products materials enriched in gypsum strong candidates for agricultural utilization.

A majority of the sulfur currently being deposited in FGD processes is in the form of sulfites. Seedlings of some crop species grown in the presence of significant amounts of sulfites are not benefited as they are with sulfates and actual growth reductions have been observed (R. B. Clark personal communication). Increased oxidation in the FGD process can result in the production of sulfates rather than sulfites. However, pilot plant estimates indicate that this will add about \$4 per ton to the cost of the sulfur by-product.

Another avenue would be to wait till natural processes oxidize the sulfites to sulfates. The somewhat gelatinous nature of the sulfite by-product hampers drying and invasion of the stored by-product by the air phase. Consequently the rate of oxidation of sulfites stored in large stockpiles is generally extremely slow and often practically negligible. On the other hand, when the sulfites are applied to soils there are indications that the rate of oxidation increases rapidly. Whether this is due to better access to oxygen or the inoculation of the sulfite by oxidizing organisms from the soil is not known, but there are indications that the sulfite can oxidize to sulfate within a few weeks. Timing the application to soils to allow oxidation to take place prior to plant growth may facilitate conversion of FGD sulfite bearing materials to sulfates. Properly managed oxidation in the soil might then change the hundreds of millions of tons

of FGD sulfite-bearing materials which are currently stockpiled as a physically hazardous waste into a sulfate resource with significant value.

Effect on soil physical properties A number of soil physical and related properties have been positively affected by the use of coal combustion by-products. Improved soil texture (Chang et al., 1989) with concomitant increase in aeration and reduced bulk density result from application of silt-sized coal combustion by-products. Although increases in water-holding capacity in some soils have been reported from some ash applications, it is unclear whether this effect translates directly into increased available water for plant growth. The existing literature is not clear on this point.

However, an interesting study on water relations and ash application was performed by Jacobs et al., 1991. They banded ash into the soil at a 45° angle to the surface. Corn roots were concentrated at the ash-band which was saturated following a rain event. Overall, corn yields increased in the ash-banded plots.

The pozzolanic activity of some coal combustion by-products can be viewed as either a positive or negative attribute. Ash materials which exhibit pozzolanic activity have been shown to reduce soil hydraulic conductivity as well as root growth. These effects can be lessened by using weathered materials or lower application rates. Additionally, as noted above, banding ash into the soil can avoid these problems. No reports have been made on the trenching of coal combustion by-products in agriculture. Current studies are underway (Korcak, unpublished data) examining trenching (15 cm wide by 120 cm deep) of FBC materials alongside tree rows in establishing apple orchards. The purpose is to prevent lateral root growth in order to initiate early fruit bearing and to reduce soil volume exploited by the root systems in order to facilitate management of tree nutrition by fertilization. Additionally, trenching will allow tree roots the alternative of growing into the fringes of the FBC trench to pick up needed calcium, sulfate, and micro nutrients or staying away from the relatively high concentra-

tions of these elements if they are deleterious to root growth.

The soil 'cap' technique noted earlier also probably has a positive effect on precipitation use efficiency. A 'cap' of by-product increases sustained infiltration rates, reduces transpiration by weeds (Korcak unpublished data), reduces evaporation losses from the soil surface (K. D. Ritchey personal communication) and increases rooting depth in acid soils (Sumner et al., 1990) thereby increasing plant water use efficiency. The resulting improvement in water use efficiency and consequent reduction in water stress on the crops would probably be beneficial in practically all of the crop producing areas of the U.S.A.

High sodium containing ash or FGD by-products may present a potential sodicity hazard with accompanying soil dispersion and reduction in infiltration rates. Application of by-products high in sodium in dry climates, even if mixed in the soil, could create sodicity as the sodium is carried and deposited to the surface. This could also be a potential hazard in humid areas particular over longer time periods. Consequently, highly sodic materials should generally be identified and their application to agricultural soils should be avoided.

Overall, effects of coal combustion by-products application in agricultural soils should be beneficial on soil physical properties if the type of materials are well characterized before use and highly sodic materials are avoided. In fact, some of the major advantages of coal combustion by-products may be in the area of enhanced soil water availability for plant growth. This needs additional evaluation.

Effect on soil microbiological properties

The microbiology of the soil/plant system as affected by ash application has received the least emphasis by researchers. Most of the research performed to date has examined either soil microbial activity or soil respiration activity (e.g. Cervelli et al., 1987; Pichtel and Hayes, 1990). Results of these and other studies are generally inconclusive although there is a tendency for reduced soil respiration and microbial number following ash application.

The exact cause of this response has yet to be firmly elucidated.

Amelioration of reduced soil microbial activity may be made by simultaneous addition of an organic amendment such as sewage sludge (Pichtel and Hayes, 1990). The ratio of organic carbon to nitrogen in soils has a significant effect on soil microbiology. Little or no nitrogen is supplied by ash materials, and the carbon content varies depending upon the particular ash by-product. Normally, most carbon in these materials is inorganic and would have little direct effect on microbial activity in any case. The effect of applied ash on the equilibrium soil carbon:nitrogen ratio requires more research. Additionally, the effect of higher carbon levels in some coal combustion by-products as well as the effects of co-utilization with an organic source (e.g., sewage sludge, manures, newspaper, etc.) should be evaluated in the future.

Utilization of bottom ash It is worth singling out conventional power plant bottom ash as a potential soil amendment since this material represents one of the more useful coal combustion by-products for agriculture. These granular materials are generally applied at rates at or near the lime requirement for the particular soil. They have a positive effect on soil texture and a modifying influence on soil pH.

Recently, a management plan for the agricultural utilization of bottom ash has been proposed (Sell et al., 1989). This plan incorporates an economic analysis for agricultural utilization which shows that there is a 62% savings for land spreading versus conventional landfill disposal.

There is a need to develop additional land management plans, perhaps on a state-by-state basis, for the agricultural utilization of bottom ash, taking into consideration soil type, crops grown, and climatic factors.

Utilization of FBC and FGD residues Research has been conducted on the agricultural utilization of fluidized bed combustion (FBC) by-products but no reviews are available. Past research is summarized below. It is difficult to discern in many reports on the utili-

zation of FBC materials whether the material used was spent bottom ash or a combination of spent bottom ash and captured fly ash. The research has generally involved rates equal to the lime requirement of the soil or multiples thereof. Crops studied include corn and peanuts (Terman, 1978), peaches (Korcak et al., 1984; Edwards et al., 1985), forages (Stout et al., 1979), and apples (Korcak, 1979; 1980; 1982; 1984; 1985; Wrubel et al., 1982). FBC residue was also used as an amendment for acid mine spoils (Sidle et al., 1979).

Utilization of high application rates of FBC materials is limited by the high alkalinity produced when the material is mixed with the soil (Terman, 1978). Mays et al. (1991) incorporated FBC by-products at rates of 0, 20, 102, and 508 Mg ha⁻¹ for corn, soybeans, tall fescue (*Festuca arundinacea*), and alfalfa (*Medicago sativa* L.). Annual application rates up to 20 Mg ha⁻¹ or a single application of 102 Mg ha⁻¹ had no adverse effects on the yield of any of the crops tested. The highest rate led to crop failure primarily due to high soil pH and very high levels of soil calcium and sulfur. The pozzolanic nature of the by-product created large chunks of the material in the field.

The data base on agricultural utilization of FGD materials, particularly un-oxidized materials, is sparse. Compared to FBC materials, un-oxidized scrubber sludges will probably require more careful monitoring and application rates and beneficial agricultural use will be at lower rates. Most scrubber sludges contain some fly ash and fly ash is often added at the end of the waste stream to aid in stabilization of the slurry (Terman, 1978). Scrubber sludges must also be kept from reaching an anaerobic stage due to the potential for generating hydrogen sulfide gas (Raiswell and Bottrell, 1991).

FGD sludges oxidized at the plant result in material that is high in CaSO₄ • 2H₂O (gypsum); if they are not oxidized, CaSO₃ (calcium sulfite) predominates (Terman, 1978). Calcium sulfate is an agriculturally valuable product, widely used to supply calcium to peanuts in a soluble form. (see Appendix A) It also has potential for decreasing sub surface soil acidity and increasing plant rooting depth

and drought tolerance. The dissolution of several gypsum-containing FGD materials was compared to PG and mined gypsum (Bolan et al., 1991). The FGD materials were 99+% pure gypsum while the Pg was 97.5% gypsum compared to 82.5% gypsum in the mined material. The overriding difference was the higher content of CaCO_3 in the mined gypsum, 12.4%. All of the FGD materials and the Pg had higher dissolution rates than the mined gypsum. Dissolution of all samples was three to eight times faster in the presence of soil than in water.

Gissel-Nielsen and Bertelsen (1988) evaluated a number of FGD products in trials with barley (*Hordeum vulgare*). One of these contained 10% SO_3^{2-} , 24% SO_4^{2-} , 8% fly ash, and 0.5% NO_3^- . Although not noted, the high amount of sulfate present apparently indicates some oxidation of the material. They noted that plant selenium concentrations were increased from 0.05 mg kg^{-1} in the control to 0.18 mg kg^{-1} at the highest application rate, 0.5% by weight, of coal-derived FGD. At these concentrations, selenium in plants is considered an adequate source of selenium for animal nutrition.

Scrubber sludge containing $4.1 \text{ g boron kg}^{-1}$ was utilized as a boron source to correct a boron deficiency on a loamy sand soil (Ransome and Dowdy, 1987). Soybean yields were decreased during the first application year with the 10, 20, 40 $\text{Mg scrubber sludge ha}^{-1}$ applications due to elevated salt content. Yields were enhanced by scrubber sludge at all rates by the third year. Adequate soil boron for soybean growth was achieved by the 20 Mg ha^{-1} application rate. The type of scrubber sludge, whether oxidized or not, was not indicated. They also express a need to determine the location of boron that was apparently leached out of the root zone or otherwise inactivated.

There is a continuing need to examine the potential for the utilization of FGD by-products in agriculture. FGD materials currently being produced, particularly dry, oxidized materials are among those coal combustion by-products best suited for agricultural utilization. Research is currently underway to examine some of the wet FGD

by-products which are high in calcium sulfite (K. Ritchey and R. Clark, personal communication). These studies as well as studies involving new by-products coming on-line are needed.

Recommendations

*A coal combustion by-product data base should be developed to incorporate agriculturally important parameters. Existing engineering data bases are not readily applicable. The data base would assist in the selection of the most appropriate coal combustion by-products for agricultural utilization.

*Cooperative work should be initiated with the appropriate agencies and industry in order to evaluate new Clean Air technology-based by-products as these technologies are being developed. This research needs to be conducted in several climatic zones with different soil types.

*Mineralogical data is needed on the fate of coal combustion by-products in the soil environment. Studies should be initiated at the laboratory and field level to ascertain fate of potential contaminants. Old agricultural sites previously treated with coal combustion residues should be identified and evaluated.

*Assay techniques to identify potentially hazardous by-products should be developed. Such assays should be plant-oriented, simple to perform and short term. Parameters to be assayed should include soluble salts, trace element phytotoxicities, and excessive alkalinity.

*Application methods should be evaluated including surface incorporation, banding, trenching, and surface 'capping'.

*Coal combustion by-products which contain significant amounts of gypsum should be examined as potential soil amendments. Research should complement reported and ongoing work on mined gypsum and Pg.

*Studies should be initiated to examine the potential benefits of mixtures and/or composts of coal combustion by-products and other waste streams. In many cases it appears that these mixtures would enhance the agronomic value of the by-products.

*A better understanding of the chemical behavior of sulfite in the soil environment is needed in order to manage agricultural use of wet scrubber-type flue gas desulfurization by-products which contain significant amounts of sulfite.

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II. Phosphogypsum

Summary

Production of phosphogypsum in the United States totals about 36.3 million Mg (40 million tons) per year. Stockpiles in Florida, the largest phosphogypsum producing area, are approaching 545 million Mg (600 million tons). Approximately five tons of phosphogypsum are produced for each ton of phosphoric acid manufactured. Unlike coal combustion residues, phosphogypsum is produced in relatively few areas nationally: Florida, Louisiana, Mississippi, North Carolina, Idaho and Wyoming. Agricultural utilization of phosphogypsum has been studied and evaluated as a calcium and/or sulfur plant nutrient source and as a gypsum soil amendment.

Primary concerns with phosphogypsum center around environmental issues related to fluoride and radium levels. Although variable, south Florida phosphogypsum tends to have the highest radium concentrations.

Limited research has been performed on mixtures/composts of phosphogypsum. This area of research could be expanded. One of the constraints on extensive use of phosphogypsum is the localization of the industry.

A. Overview

Phosphogypsum (PG) is a by-product of the phosphate fertilizer industry emanating from the production of phosphoric acid from rock phosphate. Production of PG in Florida is estimated to be 27.2 million Mg annually (Hunter, 1989). The composition of PG (Table 2-1) varies depending upon the source of rock phosphate and the particulars of the phosphoric acid manufacturing process (Mays and Mortvedt, 1986). PG material normally has an aqueous pH between 4.5 and 5.0. Within the last two years the agricultural use of PG was suspended by US EPA which had reduced the level of allowable radioactive radium-226 and associated radon production by a factor of five, which put some of the PG into the non-allowable category (U.S. Gypsum Co., 1990). A more recent ruling by the U. S. EPA (Federal Register, 6/3/92) permits the controlled use of PG in agriculture if radium-226 levels are $<10 \text{ pCi g}^{-1}$. This restriction on the maximum radium radioactivity essentially eliminates the use of southern Florida PG since its radium-226 levels are commonly in the 15 to 25 pCi g^{-1} range but should not impact PG from northern Florida or North Carolina

Table 2-1. Approximate elemental composition of phosphogypsum.^a

Major Constituents (%)			
Calcium	---- 20 - 24	Phosphorus	0.1 - 0.5
Sulfur	---- 15 - 19	Fluorine	-- 0.5 - 3.8
Minor Constituents (mg kg ⁻¹)			
Potassium	---- 100-800	Magnesium	---- 8-400
Molybdenum	---- 65	Cadmium	----- 0.23
Radioactivity			
²²⁶ Ra ----- 10- 25 pCi g ⁻¹ ^b			

^aValues presented are an average from the following sources: Mays and Mortvedt, 1986; Pavan et al., 1987; Lin et al., 1988; Alva and Sumner, 1989; Alva, et al., 1990; Sumner, 1990.

^bValue of Mays and Mortvedt, 1986 for southern Florida phosphogypsum only.

which generally has lower radium-226 levels (S. Richardson, Fla. Inst. Phosphate Res., personal communication).

B. Agricultural Utilization

The fate of radium-226 in Florida PG was investigated by Mays and Mortvedt (1986). They surface-applied PG containing $25 \text{ pCi g}^{-1} \text{ }^{226}\text{Ra}$, at rates up to 112 Mg ha^{-1} to a silt loam soil and successively grew corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.) crops. Application of PG even at the 112 Mg ha^{-1} rate had no effect on the radioactivity levels in grain of corn, wheat, or soybeans. The 112 Mg ha^{-1} PG used in this study was more than 200 times the normal rate of gypsum used for peanut fertilization. Additionally, they noted no increases in grain cadmium levels but there was, at the 112 Mg ha^{-1} rate, a growth depression on corn which was ascribed to an induced calcium-magnesium imbalance.

Numerous studies have shown that PG can alleviate some detrimental effects of subsoil acidity on plant growth (Alva and Sumner, 1989; Alva et al., 1990) when surface applied (Caldwell et al., 1990) or subsoiled (McCray et al., 1991). Sumner (1990) concluded that there was essentially no difference between mined gypsum and PG regarding correction of subsoil acidity problems.

The implanted soil-mesh bag technique was used by Lin, et al. (1988) to examine the effect of PG versus lime on alleviating poor root growth on a Spodosol B_h horizon soil. Amended soil in mesh bags was implanted around mature orange trees and sampled for periods up to 139 days. Bags containing B_h horizon soil amended with lime had significantly higher root densities than control soils while root densities in PG amended soil bags were not significantly different than the control. In this study, PG did not decrease exchangeable aluminum compared to control soils.

PG application to apple (*Malus domestica* Borkh.) trees grown on two Brazilian soils, both low in calcium and one high and one low in aluminum, were compared to lime,

calcium chloride, and magnesite (a magnesium-lime material) (Pavan et al., 1987). PG and lime significantly increased rooting density in the surface of the high aluminum soil and this effect extended to a depth of 60 cm only with PG application. PG or lime application significantly increased fruit size and yield compared to other treatments, reflecting the enhanced rooting and increased water supply to the trees.

Sumner (1990) compared surface-applied gypsum to mechanical mixing or mechanical mixing plus lime on Southeastern U. S. soils. Peaches grown on a coarse sandy loam soil with an argillic horizon in the subsoil exhibited only a slight response to surface gypsum application when compared to either mechanical treatment. The lack of response to gypsum was accredited to the greater sensitivity of peach roots to physical rather than chemical barriers in the subsoil. Several trials with agronomic crops showed no difference between mined gypsum and PG.

Recommendations

*The primary research needs are studies on fluoride and radium-226 contamination potential from PG utilization to provide a factual basis for maintaining or revising the current limits which keep a major portion of the calcium and sulfate by-product of the phosphate industry from being used.

*One unexplored research thrust is mixtures/composts of PG and other by-products to expand marketing potential in agriculture. Documentation is needed on the potential benefits of combining PG with an organic matter source particularly on the mobility of calcium in the soil system.

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III. Other Industrial By-products

Summary

Every industry creates a waste stream. The potential for agricultural utilization will vary on a case by case basis. Many of these by-products have been examined previously for their potential for utilization in agriculture. However, some other urban and rural-oriented by-products have not received attention. These include residues from concrete manufacturing and fines accumulated from the production of sand and gravel and stone crushed aggregates. Materials such as these may be utilized in more urban-oriented agricultural situations. There is a need to evaluate and characterize these types of by-products and examine potential benefits/hazards.

Other industrial by-products which have previously been studied are included since new information is available on their benefit/ hazards in agricultural utilization. These include leather manufacturing by-products calcium silicate slag, and wood ash.

A. Overview

The following subsections present a brief examination of a variety of industrial waste streams. Only those industrial waste streams that have changed recently or for which significant new data has accumulated over the past ten years are included. Also included are some by-products that have received little if any attention in the past. References such as Parr et al., 1983 and U.S.D.A., 1978 provide information on industrial wastes not covered in this report. Industrial wastes covered in these reports, but not included here are: petroleum, pharmaceutical, pulp and paper, soap and detergent, munitions and explosives, pesticides and organic chemicals, textiles, wood preservatives, milling, meat packing and canneries.

Of interest are those industrial wastes that are more urban-oriented and that have not received attention in prior reports. These by-products include residues from concrete manufacturing and fines from the production of rock aggregate. Although these industries may not always be urban-oriented, many are, and most of these by-products may present little if any hazard in agriculture utilization per se or as components of mixtures or composts for agricultural utilization.

B. Leather Manufacturing Wastes

Leather manufacturing generates about 150,000 Mg (165,200 tons) of dry sludges annually (U. S. Environmental Protection Agency, 1976). Basically, three types of wastes are produced: solid wastes from splitting and trimming hides; sludges from liming, dehairing, pickling, and chrome tanning; and liquid waste waters from throughout the operation (Hughes, 1988).

The primary agricultural constraint on the utilization of by-products from leather has been the chromium content of the sludges. Currently, most processing plants are recycling the chromium within the facility which decreases the amount of chromium leaving

the plant. This recycling segregates high chromium waste streams from the other waste streams in the manufacturing process.

Chromium has been of concern due to its potential plant toxicity. Trivalent chromium (CrIII or chromic) which is present in the sludges is not toxic to plants and is immobile in the soil system. However, hexavalent chromium (CrVI or chromate) is phytotoxic and mobile. The possible oxidation of chromium to the mobile form and the potential for phytotoxicity has been the concern of most agricultural utilization-related research (Chaney, 1983).

Another potential problem is the salinity of the waste water generated. This salinity originates from salt present in the hides prior to tanning. Untreated, this waste water is unsuited for agricultural utilization. This problem may be circumvented by composting the waste water and sludge. Under high rainfall regimes leaching occurs and salinity of the compost decreases to acceptable levels.

Dewatered tannery sludge has nitrogen contents ranging from 2.5 to 5%. When chromium has been adequately excluded from these sludges the optimum application rates should be based on nitrogen needs of the crops to be grown. This approach avoids leaving substantial nitrates in soil solution during times when it can be leached into ground water supplies (Stromberg et al., 1984).

Recommendations

*The isolation, recycling and identification of those in-house waste streams high in chromium should be pursued and these materials segregated for separate disposal.

*Application rates of leather processing wastes to soils should be based on nitrogen content and crop nitrogen demand to reduce nitrate leaching.

*Basic research on the environmental oxidation of chromic to chromate is needed to better understand and predict long term chromium hazards.

C. Calcium Silicate Slag

Calcium silicate slag is a by-product of the electric furnace production of phosphate from apatite ore. The material has a calcium carbonate equivalent of almost 50% and contains trace amounts of unrecovered phosphorus along with calcium, magnesium, and potassium plus plant micronutrients. However, the silicon content of the material has drawn the most research attention.

Sugar cane and rice are known to respond to supplemental silicon for maximum yields (Anderson et al., 1992) and calcium silicate slag, containing about 200 g kg^{-1} silicon has been utilized successfully as a silicon source. In addition to yield increases Raid et al. (1992) reported enhanced resistance of sugar cane to the foliar disease, ringspot. They hypothesized that the increased uptake of silicon, from calcium silicate slag, into the leaves helped to create a penetration barrier to certain attacking insects which are disease carriers.

Concentration of unrecovered phosphorus in calcium silicate slag is usually less than 10 g kg^{-1} . However, significant amounts of phosphorus will be applied at high application rates of slag. Much concern has arisen in the Florida Everglades, where sugar cane production is high, due to the adverse environmental effects of excessive phosphorus fertilization. The fate of phosphorus applied from calcium silicate slag has been studied (Anderson et al., 1992). At application rates of up to 20 Mg ha^{-1} , slag applied phosphorus was found to be biologically inactive and not a likely source of elevated drainage water phosphorus loading.

The concern for the adverse environmental effects of increased phosphorus in waterways is not limited to the Everglades area. The potential of high calcium-containing industrial by-products, such as calcium silicate slag, to reduce solubility of phosphorus and keep its concentrations in biologically desirable ranges needs to be documented. This type of research would also be germane to other high-calcium by-products such as fluidized bed materials and flue gas desulfurization by-products from the coal combustion industry.

A potential problem with the utilization of calcium silicate slag has been identified (Anderson, 1991). In some cases, sugar cane foliar magnesium levels have been shown to decrease after slag application which can create a magnesium deficiency with resultant reduced yields. It is unknown whether this is due to a silicon/magnesium antagonism, a low soil magnesium content, or possibly an imbalance of soil calcium and magnesium due to the high calcium to magnesium ratio of the applied slag.

Recommendations

*The reactions and solubilities of phosphorus in systems high in calcium need to be determined to allow prediction of their leaching into waterways. This information would have direct application to proper agricultural use of calcium silicate slag and would provide needed insight into the benefits of mixing highly calcareous by-products with poultry manures and other products suspected of providing excess phosphorus to our waterways.

*The status of soil magnesium availability under condition of high levels of available silicon and high inputs of calcium needs to be defined in order to eliminate potential magnesium deficiency stress.

D. Incineration Ash

Incineration of municipal wastes is becoming more widespread. As of 1990 there were 70 municipal refuse incinerators operating in the U. S. with about 250 facilities in the planning stage (Lisk et al., 1989). There have been no reports on the potential for agricultural utilization of incinerator ash. However, these ash materials will become an urban problem. Most will probably be landfilled. One of the primary constraints for utilizing these types of materials will be the variability of the end-product, particularly in heavy and trace elemental contents (Sawhney and Frink, 1991).

It is assumed that the incineration processes used will vary from facility to facility thereby creating a range of ash types (e.g. acidic to alkaline). Pressures to land apply these materials will increase in the future, therefore, baseline data to identify the benefits/hazards of these different types will be needed.

Recommendations

***Cautionary Note - Incineration ashes may be classified as hazardous wastes. This would preclude their utilization as agricultural amendments.**

*A data base containing agriculturally important parameters should be initiated on the types of ash produced from different plants in order to better characterize the potential use of these materials as soil amendments.

*Studies should be initiated in conjunction with local governments to examine the potential benefits/hazards of particular ash materials as soil amendments alone and in combination with other organic and calcium-bearing municipal and industrial by-products.

E. Concrete Manufacturing Residues

Approximately 1.8 Mg (or 1 cubic yard) of concrete are produced each year per person in the United States and about 2 to 4% of this amount, 36.3 to 72.6 kg per person, is waste. A portion of this waste originates from the solid materials (aggregates used in the concrete) rinsed from delivery trucks. This material is alkaline and high in calcium silicates.

A preliminary investigation of this solid material remaining from rinsing trucks is underway (Korcak, unpublished data). Initial results indicate that the material is not phytotoxic even at rates up to 224 Mg ha^{-1} when surface applied. As a result of its alkaline and calcareous nature, it appears to have some potential as a liming agent.

The material is representative of an urban by-product that may be utilized in agriculture or be a component of an urban waste mixture. In the Washington-Baltimore corridor it is estimated that about 9,000 Mg of this material is produced annually.

Recommendation

*The potential benefits/hazards of concrete residues should be identified. Due to the urban origin of these materials their potential as components of composts or mixes with other municipal and industrial by-products should be explored.

F. Aggregate Industry Fines

Annual production of aggregate (sand, gravel, and crushed stone) in the U. S. is about 1.8 billion Mg (R. Meininger, personal communication) and about 5-10% of this total is waste fines. These fines range in size from fine sand to clay and are collected in settling ponds. This industry is diverse due to the large number of plants in the United States (Tepordei, 1987) and the particular type of rock that is crushed (Tepordei, 1992). The resultant fines will therefore vary dependent upon rock type.

A number of attempts have been made and are currently under investigation to utilize these materials. Some of the recycled fines are being used to create a manufactured top soil by mixing with an organic material (e.g., sewage sludge) or by composting with municipal refuse.

Enhanced availability of nutrients which stimulate root growth (vegetable, tree, or other crops) is indicated by proliferation of roots in new fractures in rocks. Increased plant growth resulting from incorporating fines from rock crushing operations into soils may result from a similarly enhanced nutrient availability. In both cases, interactions of root exudates with the newly fractured mineral surfaces may be a significant or major factor in mobilization of nutrients from the minerals for plant uptake. Information on the solubilization from freshly cleaved mineral surfaces by water and on the interactive chemistry of such surfaces with root exudates, or organic chemicals of the type exuded by roots, is needed. This information will assist in understanding and predicting the benefits and possible hazards of agricultural use of freshly crushed fine materials or fines at deposit depths that have not been demineralized by plant growth or acid leaching.

Recommendations

*Agricultural studies are needed to delineate the potential benefits/hazards of utilizing waste fines either as a soil amendment or as a component of potting mixtures or in composting operations.

*Solubility should be determined for constituents of freshly cleaved mineral surfaces in water, with and without interactions with organic compounds of the type exuded by plant roots. This data base should then be used to help understand and predict potential benefits and hazards resulting from agricultural and landscaping use of fines from mineral crushing operations.

*Perform a literature search of European and other countries that have executed technical studies on the performance of glacial and other types of gravel and rock fines when used to remineralize soils in forests and other agricultural applications.

G. Wood Ash

The combustion of wood waste as fuel for steam production and/or generation of electricity creates localized sources of ash. Utilization of wood waste in these processes has and will increase due to stricter regulations on open burning or landfilling as well as with increased costs of landfilling these materials. An industry rule-of-thumb is that bark from one million board feet of logs will provide one ton of ash. This equates to more than 908 Mg of ash generated annually in western Montana (Host and Pfenninger, 1978). Nationally, 1.4 to 2.7 million Mg of ash are produced yearly from combusting wood wastes from paper mills and saw mills (Campbell, 1990).

Ash composition varies with the source of waste wood. Etiegni and Campbell (1991) reported Lodgepole pine sawdust ash with a pH about 13 which contained (in %) 18-26 calcium, 6-9 magnesium, 0.4-11 potassium, and 1.7-2.5 phosphorus. They studied the effect of temperature on ash combustion and found calcium, magnesium, and phosphorus increased with increasing temperature while potassium decreased. Schreiner et al. (1938) note that some unleached hardwood ashes can contain upwards of 6% potash, 2% phosphoric acid, and 30% lime.

A number of studies performed on utilization of wood ash in agricultural situations have been recently summarized (Campbell, 1990). The primary benefits of wood ash are lime potential and as a source of potassium plus other macro- and micro-nutrients. Application rates based on the soil lime requirement should present little risk to the environment.

Recommendations

* Sites where wood ash has been used in the past should be re-evaluated particularly to examine the fate of ash-applied trace elements.

* A survey of state regulations on the use of wood ash in agriculture should be performed. This data base could then be used in development of guidelines for other ash streams such as those emanating from selected coal combustion by-products and municipal incinerators.

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Appendix A

The Role Of Gypsum In The Soil/Plant System

A. Overview

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) occurs geologically as an evaporite mineral associated with sedimentary deposits. The most important property of gypsum relating to agricultural applications is its solubility. Although sparingly soluble in aqueous solution (2.5 g L^{-1}), gypsum is more soluble than calcite (CaCO_3) (solubility in water - 0.15 mg L^{-1}) (Finck, 1982). The ascribed benefits of gypsum on soil chemical and physical properties and resultant benefits to crops are summarized in Table A-1. Recent reviews on the utilization of gypsum in agriculture have been published (Oster, 1982; Shainberg et al., 1989). However, the majority of the cited lit-

Table A-1. Potential benefits of gypsum in the soil/plant system.

Soil Benefits	
Physical	Chemical
Increased infiltration	Increased subsoil Ca
Increased aggregation	Reduced exchangeable Al
Reclamation of sodic soils	
Reduced root impedance	
Reduced restriction of hardpans	
Plant Benefits	
Ca and S nutrient source	
Deeper rooting	
Increased tolerance to drought stress	
Ca source without increasing soil pH	
Long term effects	

erature in these reviews involves agronomic crops.

B. Soil Physical Properties

The ameliorative effect of increased surface infiltration from surface-applied gypsum on dispersive and sodic soils is well documented (Kemper and Noonan, 1970; Shainberg et al., 1989; Roth and Pavan, 1991). Applied gypsum decreases the percentage of sodium adsorbed on the soil and increases the free electrolyte concentration which reduces dispersion and favors flocculation and aggregation of soils (U.S. Salinity Lab. Staff, 1954). In high sodium soils, with a pH between 8.5 and 10, applied gypsum raises the soluble calcium concentration to levels greater than that of calcite, thereby precipitating calcite. In turn, pH is reduced to 7.5-8.0 and calcite and gypsum coexist. The higher soluble calcium concentrations lead to enhanced flocculation of soil colloids (Lindsay, 1979).

The effect of surface applied gypsum (10^4 kg ha^{-1}) on subsoil mechanical impedance 2.5 years after application to peaches (*Prunus persica* L.) was studied by measuring changes in cone penetrometer index (Radcliffe et al., 1986). A significant reduction in mechanical impedance was noted to a depth of 0.55 m within this relatively short time frame. The marked improvement in root penetration resulting from the applied gypsum appeared to be more directly related to increased calcium supplied by gypsum which is known to be essential for rapid meristematic root growth. Greater root activity produces organic matter which aids in aggregation, and induces

invasion of beneficial mesofauna such as earthworms whose burrows facilitate movements of water, oxygen, and carbon dioxide essential to crop growth.

C. Soil Chemical Properties

The correction of subsoil acidity has received attention because of its significant effects on plant rooting and the worldwide occurrence of the problem. The primary factor associated with subsoil acidity is the high level of phytotoxicity of exchangeable aluminum and to some extent, exchangeable manganese. In most cases these high levels of aluminum and manganese are related to levels of calcium that are deficient (McCray and Sumner, 1990).

Amelioration of subsoil acidity problems and corresponding increases in rooting depth, enhanced root calcium relationships, and resistance to drought have been shown (Sumner and Carter, 1988). Both negative and positive results on plant responses have been reported (Alva et al., 1990) indicating that the chemistry of gypsum in the soil system is not yet completely understood (McCray and Sumner, 1990).

D. Crop Responses

Gypsum provides both calcium and sulfur for crop nutrition. Gypsum has long been used as a calcium source for peanuts (*Arachis hypogaea* L.) which have a unique calcium requirement during pod development (Alva et al., 1989), depending on peanut type (Gaines et al., 1991), soil calcium status (Alva et al., 1991), and type and form of applied gypsum (Alva et al., 1989). Repeated annual applications of gypsum to peanuts have raised a concern for proper phosphorus nutrition (Sistani and Morrill, 1992) since build-up of excess calcium in soil may lead to reduced availability of phosphorus by formation of calcium phosphate.

Gypsum increased cauliflower (*Brassica oleracea botrytis* L.) tissue calcium levels but

had no effect on reducing tip burn, a physiological disorder commonly ascribed to inadequate calcium nutrition (Rosen et al., 1987). The importance of gypsum being more soluble than calcite was shown by Carter and Cutcliffe (1990) in Brussels sprouts (*Brassica oleracea gemmifera*) grown at one site low in soil calcium. Tissue calcium levels and marketable yields were significantly elevated during the first growing season after application.

Gypsum was used as a calcium source for blueberry (*Vaccinium* sp.) on upland mineral soils in order to determine the effect of calcium without significantly affecting soil pH (Korcak, 1992). Although the blueberry is considered an acid-loving plant, the results indicate at least short-term tolerance for increased soil calcium from gypsum. The practicality of using gypsum to enhance root tolerance to high soil aluminum in acid upland soils is under further study.

E. Summary

The agricultural use of gypsum has primarily been in the reclamation of sodic soils. Using gypsum as an amendment for acid subsoils is of recent vintage (Shainberg et al., 1989). Research continues on the chemistry of gypsum in the soil/plant system and resultant effects on soil chemical/physical properties and crop responses. The greater mobility of calcium derived from gypsum versus calcite requires the input of sufficient water for solubility/movement. However, in many areas where subsoil acidity problems occur, i.e. the southeastern U. S. and the humid areas of South America, adequate percolation of water occurs. But there have been problems created by the continuous applications of gypsum or in the use of high surface application rates (Table A-2). The occurrence and extent of the problems listed in Table A-2 will vary with the particular soil/plant system under study. For instance, surface application of gypsum increases leaching of magnesium and potassium. The induced leaching of magnesium and potassium by gypsum in the fruit zone is beneficial to peanuts (Alva and Gascho, 1991). Surface application of a high gypsum content by-product within orchard tree rows resulted in sufficient leaching of magnesium

over a 6-year period to reduce foliar magnesium concentrations in apple trees to near levels where supplementation would be needed (Korcak, 1988).

Although no standardized test is presently available to calculate gypsum treatment levels (Table A-2), Sumner (1990) has proposed a soil test for responsiveness to gypsum". The test is based on the fact that soils which show favorable response to gypsum also exhibit substantial salt absorption. Calibration and standardization of such a soil test and further research on a wide range of soil types should aid in the increased utilization of gypsum as a soil amendment.

Table A-2. Potential problems in the utilization of gypsum in the soil/plant system.

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- A. Excessive soil Ca^{2+} buildup from repeated and/or high applications
 - a. Induced P deficiency
 - b. Excessive leaching of Mg^{2+} and K^{+} from surface horizons particularly sandy soils
 - B. Initial increase in soil salt content
 - C. Lack of standardized guidelines to calculate application rates
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Agricultural Utilization of Wastes: Summary

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Agricultural Utilization of Wastes:

Summary

A. Introduction

America's cities, farms and industries are producing increasing amounts of by-products and wastes. Sewage sludge and solid wastes from our cities, animal manures from our farms and coal combustion residues and other by-products from industries require environmentally safe and cost-effective methods of disposal. In the past it was cheaper to bury, burn or dump our waste rather than to find alternative methods of disposal or utilization. At present, concern for the protection of our soils, water and air has led to suspension of many of our previous methods of waste disposal.

Currently much of our municipal waste is placed in landfills, but landfill capacity is decreasing and disposal costs are rapidly increasing. Many of our urban areas have an urgent need for long-term environmentally safe methods for recycling and disposal of wastes. Our industries produce hundreds of millions of tons of by-products annually. Alternative uses have been found for a small fraction of these materials, but most industrial by-products are stockpiled at the site where they were generated. A long-term solution to this problem is needed. Many components of our animal production industry (beef, dairy, swine, and poultry) are based on animals in confinement. Huge amounts of manure are generated in a small area, creating environmental problems at the site and a major waste disposal issue. Agronomic management practices to protect environmental quality at the confinement site and to effectively utilize these manures in agricultural production systems are urgently needed.

Waste utilization problem presents a challenge and an opportunity for U.S. agriculture. We are currently confronted with the long-term goal of developing crop production practices that promote sustainability. Sustainable agriculture is characterized by plant and animal production practices that satisfy human food

and fiber needs while enhancing environmental quality and the natural resource base by making the most efficient use of nonrenewable resources and on-farm resources. Animal wastes and many municipal and industrial wastes may have substantial potential value for agricultural utilization. Selected wastes could provide plant nutrients and serve as soil conditioners. The development of methods to optimally integrate waste utilization into sustainable agricultural practices could provide a major part of the solution to urban and industrial waste disposal problems.

A number of questions need to be addressed before waste materials can be safely and economically used in agricultural systems. We need to know which materials can be land applied, how much can be applied and what are appropriate methods of application. Waste materials contain widely variable levels of nutrients, trace elements and synthetic organic chemicals. The range of concentrations of these components and their bioavailability under a variety of soil, climate and agronomic management conditions needs to be determined. This approach will help identify wastes that should not be land applied and that will require disposal under controlled conditions. Land application rates of waste materials will be dependent on bioavailability of nutrients, trace elements and synthetic organic chemicals in the waste. Application rates will have to be carefully determined to ensure that detrimental effects on environmental quality, human health, animal health and crop production are avoided. Wastes can be applied in liquid, semisolid or solid forms by spraying or spreading on the surface with or without incorporation, applied as a mulch, injected below the surface, or applied in a furrow, trough or trench. Research will need to be done to find the most effective method of application for a particular waste material from an agricultural and environmental quality perspective.

Before a waste material can be recommended for agricultural utilization a careful

risks/benefits assessment must be conducted. Research must be performed in the field using sustainable agricultural techniques. The fate and effects of nutrients, trace elements and synthetic organic chemicals on soils, plants, animals and humans must be assessed. This information is needed to address public concerns about adverse impacts associated with the use of wastes and to convince the agricultural community that it is in their best interest to utilize these materials. In addition, the specific information gained in these investigations can be used as the basis for developing regulations for land application of these materials.

A risk assessment pathway approach was successfully used to develop regulations for land application of sewage sludge. The approach involved identification of the routes of potential transfer of waste applied trace elements and synthetic organics to humans, animals, plants and the environment. Using pathway analysis and the concept of most exposed individual, the USEPA was able to establish regulations for levels of trace elements and synthetic organics in sewage sludge and to determine cumulative amounts of these components that could be land applied. This approach may need to be utilized with other municipal wastes and industrial wastes.

Although there are a variety of waste materials that could have been addressed in this report, the focus was on high volume waste streams where agricultural utilization has the potential to be a partial solution to the disposal problem. Municipal wastes (sewage sludge and solid waste), industrial wastes (coal combustion residues and other selected by-products) and agricultural wastes (animal manures) were emphasized.

B. Municipal Wastes

The U. S. has reached a critical stage in the management of our two major municipal wastes: solid waste or garbage and sewage sludge. About 182 million Mg (200 million tons) of municipal solid waste (MSW) are generated annually. This represents the equivalent of 1.95 kg (4.3 pounds) per person per day. If

current trends continue we will accumulate 202 million Mg (222 million tons) of MSW annually by the year 2000. Production of sewage sludge is approximately 7.7 million Mg (8.5 million tons) per year or the equivalent of 29 kg (64 pounds) per person annually. This is expected to double by the year 2000 due in part to new wastewater treatment requirements.

Municipal solid waste consists of a variety of components. Paper and cardboard products represent about 35% by weight of MSW. Yard wastes (20% by weight) including grass clippings, leaves, and tree and shrub trimmings constitute the next largest class of components in MSW. Metals, plastics, glass, wood and food wastes each comprise between 6 - 9% of MSW by weight. In 1991, 76% of MSW was landfilled while 14% was recycled and 10% incinerated. The general trend over the last few years has been a slow decrease in landfill disposal and an increase in the amount recycled.

The huge amount of MSW going to landfills has created a critical problem for many urban areas. Landfills are closing and the establishment of new landfills is a slow and costly process. Projections indicate that by the year 2000, there will be a 60% reduction in the number of operating landfills and a substantial reduction in landfill capacity. Landfill tipping fees which averaged \$11 per Mg (\$10 per ton) in the U.S. in 1980 have increased to greater than \$55 per Mg (\$50 per ton) in certain areas of the country and may be double current rates by the year 2000. Thus recycling and agricultural utilization of MSW are becoming economically preferable alternatives to landfilling.

The USEPA has established a goal to reduce our dependence on landfilling by source reduction and by increasing our rate of recycling (target 25% of MSW) and the amount of MSW incinerated (target 20% of MSW). They have focused on source separation and recycling of paper, metal, glass and plastics. This approach, however, will still leave vast amounts of MSW that require landfilling, so other utilization options are still needed.

Many of the components of MSW (paper, yard wastes, food wastes, wood products) are biodegradable under proper conditions and may have potential to be utilized for improv-

ing agricultural and nonagricultural land. Because of limitations associated with odors, pathogens, and undesirable chemical and physical properties, new and unstable organic wastes cannot be added directly to the soil. Composting of sewage sludge and selected components of MSW is an effective waste management process. Composting is a microbiological process that partially decomposes organic wastes through the growth and activity of mixed populations of bacteria, actinomycetes and fungi that are indigenous to the organic wastes. Farmers have been using composting for centuries to convert organic wastes into useful soil amendments. The process reduces the weight and volume of the waste while abating odors, destroying pathogens and converting nutrients to more plant available forms.

Techniques for rapid composting of sewage sludge have been developed and successfully utilized at a number of locations in the U.S. A USEPA program which features composting, land spreading and liquid injection of sewage sludge to improve agricultural and non-agricultural lands is currently in place. Standards based on concentrations of trace elements and toxic organic chemicals in sludge have been developed to regulate land application of composted and uncomposted sewage sludges. As a result of these developments only about 20% of wastewater sludges are currently placed in landfills. Although considerable progress has been made, additional land utilization of sewage sludge is possible and desirable.

A number of municipalities are composting yard wastes either alone or in combination with sewage sludge. If MSW is composted with sewage sludge it can be land applied under the regulations for sewage sludge. Research is needed to assess the risks/benefits associated with agricultural utilization of MSW so regulations can be developed for land application of these materials. Until these regulations and guidelines are developed, agricultural utilization of MSW will not greatly reduce the demand on landfill disposal. MSW composting, as currently practiced, also contributes to the demand on landfill space. In many composting operations adequate source separation does not occur prior to composting. Thus at the end of the composting process, re-

ject material ranging from 10 to 30% by volume must be screened and then landfilled. In addition many compost production facilities regard composting as a technique to reduce the weight and volume of waste rather than as a means to produce a desirable product for agricultural utilization. Therefore, a vast majority of MSW compost ends up in landfills as either cover or fill.

Sewage sludge and MSW have value as biofertilizers and soil conditioners. The biodegradable portion of MSW has average macronutrient concentrations of 0.7% nitrogen (N), 0.2% phosphorus (P) and 0.3% potassium (K). Untreated sewage sludge is similar to animal manures with average NPK contents of 4.0, 2.0 and 0.4%, respectively. In addition MSW and sewage sludge serve as sources of secondary plant nutrients [sulfur (S), iron (Fe), magnesium (Mg)] as well as micronutrients [copper (Cu), zinc (Zn), boron (B), manganese (Mn) and molybdenum (Mo)]. Favorable plant growth responses have been obtained with various combinations of composted and uncomposted MSW and sewage sludge. However, neither MSW or sewage sludge should be considered as a complete fertilizer source. Both MSW and sewage sludge, because of their relatively low nutrient contents, will need to be supplemented with fertilizers.

Another major value of municipal wastes to agriculture is their organic matter content. Organic matter is an important contribution to the health and productivity of a soil. Soil organic matter increases water infiltration rates and the capacity of soils to hold water and nutrients for use by plants. It also sustains beneficial organisms such as fungi, bacteria and earthworms which facilitate plant growth. If the organic matter level of a soil is decreased, soil degradative processes such as soil erosion, nutrient runoff and leaching losses of nutrients are accelerated. These degradative processes reduce the plant production capacity of the soil (soil productivity) and negatively impact environmental quality. Addition of municipal wastes or animal manures can increase organic matter levels in a soil which will reverse these degradative processes and enhance soil productivity.

Composting of sewage sludge and MSW can result in a stable humus-like material that is easy to handle, store and transport. These materials may have potential uses in the \$9 billion per year horticultural industry. Containerized plant production accounts for a \$4.7 billion segment of the horticultural industry. Containerized growth media typically contain 60-70% organic material. This organic fraction is currently supplied through the use of peat, milled pine bark or shredded hardwood bark. At least 40% of this organic fraction could be supplied by other sources including composted MSW and sewage sludge. However, if composted municipal wastes are to fill this need a product with a dependable standard of quality in terms of pH, soluble salts, particle size and nutrient content will have to be produced.

Soilborne diseases result in losses of more than \$4 billion annually to U.S. agriculture. Composts made from a variety of organic materials have the potential to control plant diseases caused by such soilborne pathogens as *Phytophthora*, *Pythium*, *Rhizoctonia*, and *Sclerotinia*. Currently, inconsistency in maturity and horticultural and microbial quality of composts makes it difficult for the nursery industry to rely on composts for biocontrol of specific plant pathogens. However, this use of composts has great potential if methods for predicting compost maturity can be improved and techniques developed to enhance the quality and disease suppressiveness of composts.

The safe and beneficial utilization of municipal wastes in agriculture and horticulture will depend on our ability to develop products with a known and consistent range of physical and chemical characteristics. Methods will need to be developed to improve the agronomic value of municipal wastes as biofertilizers through enrichment with fertilizers. Measures will need to be taken to segregate input components in the waste stream that may contain excess levels of toxic trace elements and hazardous organic chemicals. The fate and subsequent bioavailability of nutrients, metals and synthetic organic residues during and after composting of yard wastes and other MSW components will have to be determined.

Quality and maturity criteria need to be developed to enhance horticultural uses of municipal wastes. Methods need to be developed to dependably enhance the microbially-mediated plant disease suppression characteristics of compost and to reliably inoculate horticultural grade composts with beneficial rhizosphere microbes that can biologically mediate plant nutrient uptake. It may be desirable to mix various waste resources to produce a product with specific characteristics. This will require research to develop process technology to co-compost sewage sludges and selected biodegradable fractions of MSW.

Successful processing and agricultural utilization of municipal wastes will require consideration of the environmental issues of odor, pathogens and water quality. Control of odors and destruction of human pathogens are necessary components of a successful composting operation. Odors may be controlled by optimizing the composting process to minimize the formation of odors and by collecting, treating and dispersing odors that are formed. Biofilters have been used to treat odorous compounds and potential air pollutants in gas streams of municipal waste processing facilities. Although use of biofilters for odor control in composting facilities has increased dramatically additional research is needed to provide optimum conditions for the proliferation of the microorganisms which oxidize the odorous compounds.

Time-temperature indices have been developed for the inactivation of viruses, bacteria, fungi, protozoa and parasites in sewage sludge compost. Time-temperature criteria for destruction of human and/or plant pathogens in composts or co-composts of various types of MSW would be expected to be similar to those applicable to sewage sludge. However, research will need to be done to substantiate this extrapolation.

Agronomic practices are needed which will minimize the potential of land applied municipal wastes to degrade ground and surface water quality. Waste additions are usually based on N requirements of the crop for the growing season. However, tests to estimate the fraction of organic N that will be mineralized to plant available forms are not reliable

and N in excess of plant needs may be applied. This situation can result in leaching of nitrate to ground waters. Testing protocols are needed to assess potential mineralization of organic N in municipal wastes to allow effective agronomic management that maximizes N availability to crops while minimizing the potential for ground water pollution. Runoff of water from land amended with municipal wastes can be a major source of surface water contamination. A combination of restricted use of municipal wastes on highly erodible land and soil conservation practices such as buffer strips and stiff grass hedges should make it possible to control pollution of surface waters by nutrients and suspended solids from municipal wastes.

C. Industrial By-products

A variety of industrial wastes are produced in the U.S. The risks/benefits associated with agricultural utilization of many of these wastes including food processing wastes, industrial organic wastes, and logging and wood processing wastes were described in a previous USDA report in 1978. A number of largely inorganic industrial wastes including by-products from coal combustion, fertilizer production, the construction industry and incineration are produced in substantial amounts throughout the country. Many of these by-products have potential for utilization in agriculture, but they have not been thoroughly investigated or they have changed in composition as a result of new technology. Coal combustion by-products (CCB) are emphasized in this report because their production is rapidly increasing, coal combustion technology is changing and disposal is becoming a major issue.

Combustion of coal produces a variety of by-products including fly ash, bottom ash, flue gas desulfurization (FGD) waste, fluidized bed combustion (FBC) waste and coal gasification ash. Total production of CCB was 109 million Mg (120 million tons) in 1991 and is expected to increase to 154 million Mg (170 million tons) annually by the year 2000. Fly ash, the major by-product from coal combustion, is the particulate residue which enters the flue gas stream and is either collected by emission con-

trol devices or released to the atmosphere. Bottom ash is the residue that remains in the boiler after coal combustion. FGD wastes and FBC residues are by-products from technologies used to reduce sulfur emissions from coal combustion. FGD by-products result from post-combustion treatment of flue gases with an absorbent (calcium oxide, limestone, dolomite) to reduce SO_x discharge to the environment. FBC involves removal of SO_x during combustion of a finely divided mixture of coal and limestone on a fluidized bed created by injection of air. Production of FGD wastes and FBC residues will increase to greater than 45.5 million Mg (50 million tons) annually by the year 2000 as a result of Clean Air Act requirements for reduced S emissions. Coal gasification ash, produced during the conversion of coal into synthetic gas and liquid fuels, is similar to fly ash, but has a more coarse texture.

Fly ash and bottom ash are amorphous ferro-aluminosilicate particulate materials which contain significant amounts of Si, Al, Fe, Ca, Mg, Na and K. These ashes are enriched in trace elements compared to the parent coal and concentrations of certain trace elements such as As, B and Se increase with decreasing particle size. Ash pH, chemical properties, and physical properties vary with composition of the parent coal, combustion conditions and efficiency and type of emission control devices. FGD wastes consist of a combination of fly ash, calcium sulfite, calcium sulfate, unreacted reagent (generally calcium carbonate) and water. The chemical composition of FGD wastes will depend on the desulfurization process employed, amount of reagent used, conditions of combustion, composition of the coal source, amount of fly ash present and whether a forced oxidation of sulfite to sulfate occurs as the last step in the process. FBC produces a dry by-product that consists primarily of calcium sulfate and calcium oxide. The composition of FBC residue is dependent on many of the conditions listed for the other by-product materials.

Currently about 20% of the ash by-products (fly ash and bottom ash) are recycled. They are used in the construction industry as fill material and as components of other products such as concrete, cement and asphalt. FGD by-products are used to a limited extent

(<1% of the amount generated) in the production of sulfur-related chemicals and wallboard. Approximately 80% of the CCB produced are managed at the powerplant site. Management techniques include surface impoundments, landfills and placement in mines and quarries. On-site disposal can have a negative impact on adjacent aquatic and terrestrial systems through runoff and leaching of by-product constituents to surface and ground water. On-site disposal costs are increasing and state regulations in some areas are quite strict. Because of environmental considerations and increasing disposal costs, alternatives to on-site disposal are needed. Agricultural utilization may offer a partial solution to this problem.

Land application of selected CCB can bring about favorable changes in soil chemical and physical properties. Many of the by-products are alkaline in nature and can be used as liming materials to increase soil pH. Bottom ashes and FBC residues have neutralizing power that may be up to 90% as effective as pure calcium carbonate. Fly ash, alone or in combination with sewage sludge, has been successfully utilized in acidic mined land reclamation projects. FBC residues and oxidized FGD materials contain significant amounts of gypsum. Surface applied gypsum has been shown to be effective in ameliorating subsoil acidity. Many land areas in the eastern US have subsoil acidity problems that limit plant rooting depth. Application of high gypsum by-products to these areas could reduce subsoil acidity, thereby enhancing crop rooting depth and subsoil moisture utilization.

Although CCB are low in N and P they can serve as a source of other plant essential nutrients. High gypsum by-products have been successfully used as sources of Ca and S. Many CCB could also serve as an important source of micronutrients. Trace element deficiencies of B, Se, Mo, Cu and Zn have been corrected by the application of CCB.

Several investigations have demonstrated that improved soil physical properties result from land application of CCB. Fly ash additions to clayey soils reduced bulk density and improved aeration. The water holding capacity of sandy soils was increased by application of fly ash. Application of high gypsum by-

products can improve soil structure, increase water infiltration and reduce mechanical impedance to root growth. A soil "cap" of FBC residue under fruit trees was found to be permeable to water infiltration, reduced evaporation of soil water, and served as a physical barrier to weeds.

Plant growth limitations, food chain transfer of trace elements and water quality issues are among the problems that may be associated with agricultural utilization of CCB. These problems are related to high pH, high soluble salt content and/or high trace element levels associated with some of the by-products. High pH and soluble salt content associated with many fly ashes, FBC residues and FGD by-products can inhibit plant growth. In many cases B toxicity may be responsible. The greatest risk to plant growth occurs from application of unweathered material, since weathering tends to reduce soluble salt and B toxicity problems. High application rates of certain CCB can induce plant nutrient deficiencies. High Ca FGD by-products and FBC residues from Ca-based S removal systems can create an imbalance in the soil Ca to Mg ratio resulting in an induced plant Mg deficiency. The high level of Ca and/or Fe and Al in some by-products can result in the formation of insoluble complexes with P, thus reducing the availability of P to plants. Many FGD by-products contain appreciable amounts of calcium sulfite. When initially added to soils, calcium sulfite can inhibit plant growth, perhaps through the release of gases such as H₂S and SO₂ or through high levels of soluble salts. Sulfites are oxidized to sulfates in soils. If this oxidation can be completed prior to planting, it may be possible to add FGD by-products with high levels of calcium sulfite directly to soils. Sulfite can also be oxidized to sulfate at a cost of about \$4.40 per Mg (\$4 per ton) during the FGD process at the power plant.

Some CCB cause cementation when added to the soil thereby reducing water infiltration, hydraulic conductivity and root penetration. These negative effects can be overcome by using weathered materials, lowering application rates or applying the materials in bands. Agricultural utilization of ashes and FGD by-products containing high levels of Na should be avoided. Addition of these materials

to soils would cause soil dispersion, reduced water movement into and through the soil and sodicity problems especially in dry climates.

Relatively little is known about the influence of CCB on microbial populations and activity in soils. In general investigators have reported that fly ash addition to soil reduced microbial numbers and activity, and decreased soil respiration. The exact causes of these effects are not known although changes in soil alkalinity, salinity or concentrations of trace elements have been listed as potential factors. No consistent pattern of response has been observed when the influence of ash amendments on microbial N cycling has been studied. The influence of FGD by-products and FBC residues on soil microbial processes has not been investigated.

The most serious potential trace element hazards associated with agricultural utilization of CCB appear to be B, Se, As and Mo accumulation in soils and plants. Over-application of by-products with high levels of these elements could result in phytotoxic levels of B and elevated levels of As, Mo and Se in plant tissue. The development of methods to manage wastes to avoid potential threat to animals consuming these plant tissues merits further investigation.

Agricultural utilization of CCB could result in changes in surface and ground water chemistry through runoff and leaching of nutrients and trace elements. However, the greatest threat to water quality occurs as a result of by-product disposal in landfills and settling ponds at the power plant site. Elevated levels of soluble salts and potentially toxic trace elements including As, Ba, Cd, Cr, Pb, Hg and Se in the by-products could be leached to ground water. Only limited contamination of ground water has been observed to date at the few sites studied. However, this result may be due to the fortuitous placement of the waste at a point where the local hydrogeologic conditions limited contamination. By-product disposal in landfills and settling ponds can influence adjacent aquatic ecosystems through runoff and leaching. Effluent from stored by-products can change pH and trace element concentrations in adjacent surface waters. Fish kills and population decreases in other aquatic fauna and flora

have been linked to contamination from stockpiled CCB. Agricultural utilization of selected CCB could reduce the need for on-site disposal and thereby lower the risk to adjacent aquatic and terrestrial ecosystems.

Several of the CCB, especially those containing high amounts of gypsum, have potential for agricultural utilization. Unfortunately the agronomically important properties of many of the by-products are not well known and vary with operating conditions at the power plant. The chemical and physical properties of the by-products depend on composition of the coal, combustion conditions, method of desulfurization employed and type and efficiency of emission control devices. In addition desulfurization technologies are being developed that produce a variety of new by-products. A data base listing the major chemical and physical properties of the various by-product materials is needed to select appropriate materials for agricultural utilization. This information should include a range of values for nutrients and potentially toxic trace elements and how these levels change with operating conditions.

Information is needed concerning interactions of many of these by-products with soils before they can be safely used as soil amendments. The solubility and chemical behavior of the materials in a variety of soils and climate conditions needs to be determined. This is especially true with respect to the chemistry of high sulfite containing FGD residues in soil. A rapid plant-based bioassay technique would be useful to identify potentially hazardous by-products. Information is not available concerning the influence of many of these CCB on soil microbial populations and microbially mediated processes in soils. The bioavailability of nutrients and trace elements in CCB needs to be determined so appropriate application rates can be selected to meet plant nutritional needs while avoiding the accumulation of toxic levels of trace elements in the food chain.

The agricultural utilization of mixtures and composts of CCB with various organic wastes including sewage sludge and animal manures needs further study. Components could be mixed to address a specific soil problem or to overcome negative characteristics of

one of the waste materials. Fly ash mixtures with sewage sludge have been used to successfully reclaim disturbed lands. Some of the FBC by-products with high liming capabilities may be useful substitutes for lime in the stabilization of sewage sludges. FBC residues or fly ash could be mixed with poultry manure to tie up P from the manure and reduce the potential for its movement to surface waters. All of these potential mixtures and composts would have to be evaluated for benefits and risks since formulating a product to solve one problem may create another.

In addition to CCB a variety of other industrial by-products have potential for agricultural utilization as liming materials or nutrient sources. Three broad classes of by-product materials (residues from the P fertilizer industry, residues from the construction trades and incineration ashes) that are produced in large amounts and in general have characteristics that would not cause harmful effects if added to agricultural soils were examined in this report. In general, these materials have not been studied to any great extent, therefore benefits and risks associated with their utilization in agriculture are not well known.

Phosphogypsum is a by-product resulting from the production of phosphoric acid from phosphate rock. Approximately 36.3 million Mg (40 million tons) of this material are produced each year mainly in the states of Florida, North Carolina, Louisiana, Mississippi, Idaho and Wyoming. Large amounts of this material have been stockpiled at production sites. Phosphogypsum has been used in agriculture as a Ca and S nutrient source and as an amendment to ameliorate subsoil acidity. Utilization of phosphogypsum has been limited by environmental and human health concerns associated with fluoride and radioactive radium-226 levels in these materials. USEPA rulings have disallowed agricultural use of phosphogypsum sources with radium-226 activities in excess of 10 pCi g^{-1} . Expanded agricultural utilization of phosphogypsum will require additional research to determine if the risks associated with fluoride and radium-226 override potential benefits.

Calcium silicate slag, a by-product of electric furnace production of phosphate fertil-

izer from phosphate rock, has liming value and is a source of nutrients. Silicon in the material has been shown to increase yield of sugarcane and enhance its resistance to the foliar disease, ringspot. Application of calcium silicate slag has been shown to reduce foliar magnesium in sugarcane and may lead to magnesium deficiency at high application rates. Additional research is needed to identify other potential problems associated with agricultural utilization of this by-product.

Aggregate industry fines and concrete manufacturing residues are two industrial by-products with characteristics that may make them suitable for agricultural utilization. About 91 million Mg (100 million tons) of waste fines result from the annual production of sand, gravel and crushed stone. The solubility and plant availability of nutrients in these materials should be enhanced although the composition will be dependent on rock type. Aggregate fines have been mixed with sewage sludge or composted municipal solid waste to create a manufactured top soil. Research is needed to determine the solubility behavior of aggregate fines from different rock types in a variety of soils. This approach would allow an assessment of potential nutrient and trace element availability from these materials and provide a basis for selecting appropriate application rates.

Approximately 9.1 million Mg (10 million tons) of concrete manufacturing residues are generated, primarily in urban areas, each year in the U.S. A portion of this residue represents solid materials rinsed from concrete delivery trucks. The material is alkaline and has a high calcium silicate content. It should be useful as a liming material and would be expected to have some common characteristics with calcium silicate slag. Concrete manufacturing residues have been surface applied to soils at rates up to 224 Mg ha^{-1} (100 tons acre^{-1}) without causing phytotoxic effects. Since this material has an urban origin, it may be useful in mixtures with municipal wastes. Additional research is needed to characterize the potential benefits and risks associated with agricultural utilization of this material.

Ash from the combustion of wood waste and from the incineration of municipal waste

represent growing disposal problems. In 1990 there were 70 municipal refuse incinerators in operation in the U.S. with about 250 facilities in the planning stage. Most of the incineration ash is currently being landfilled. This material is likely to be quite variable in composition, particularly in regard to trace element levels. Potential problems with elevated trace element levels in incineration ash will probably preclude its use in agriculture.

Burning of wood waste for steam and/or generation of electricity produces between 1.4 and 2.7 million Mg (1.5 and 3.0 million tons) of ash annually. Utilization of wood waste in this manner is likely to increase because of restrictions on open burning and increasing costs of landfill disposal. Wood ash generally has value as a liming material and as a source of nutrients, although composition of the ash will vary with wood source. Some types of wood ash have been reported to have elevated levels of Cd, but application of wood ash to soils at rates equal to the lime requirement should not pose a problem.

D. Animal Wastes

Up to this point the role of agriculture as a consumer of municipal and industrial wastes has been considered. Agriculture is also a major producer of waste materials including crop residues, animal manures, dead animals and food processing wastes. Approximately 363 million Mg (400 million tons) of crop residues are produced annually. Crop residues generally do not pose an environmental problem because they are left in the field where they are valuable in terms of nutrient cycling and soil and water conservation. Huge amounts of animal manures are generated each year in the U.S. These manures can be a valuable resource if they are wisely recycled as a source of nutrients for crops, as soil conditioners and for other uses such as refeeding and methane generation. Animal wastes, especially those associated with confined animal production, if improperly handled, can result in significant degradation of soil, water and air quality.

Cattle, poultry and swine are the major sources of animal manure production in the U.S. There were approximately 99 million head of cattle and calves in the U.S. in 1990. Approximately two thirds of these animals are kept on pasture and rangeland where their manure is dispersed across a large area. This manure decomposes on the soil and in general does not cause an environmental problem, although surface water contamination by manure from grazing animals does occur. Environmental and animal waste management problems are greatly increased when a large number of animals are concentrated in a small area as is the case in feedlot and dairy operations. There are at least 10 million head of beef cattle on feedlots at any one time. Beef cattle feedlot operations are generally large (84% of the feedlots have a capacity in excess of 1000 head) and are concentrated in the states of Nebraska, Texas, Kansas, Iowa and Colorado. Annual manure production by beef cattle on feedlots was estimated at 24.1 million Mg (26.5 million tons) of solids. There were 10.2 million dairy cattle in the U.S. in 1990 with an average herd size of 98 animals. Approximately 50% of the dairy cattle are found in the states of Wisconsin, California, New York, Minnesota and Pennsylvania. Dairy cattle in confinement are estimated to produce approximately 19.1 million Mg (21 million tons) of solids annually. If improperly managed the large amounts of manure associated with beef feedlot and dairy operations can create significant environmental problems including human health issues associated with contamination of surface and ground water.

Increased demand for poultry products has led to a rapid expansion in the industry. In 1990 approximately 6.5 billion chickens and turkeys were produced on farms in the U.S. with major production occurring in Arkansas, Georgia, Alabama, North Carolina and Mississippi. The poultry population can be divided into the following categories: broiler chickens, 5966 million; layer chickens, 272 million; and turkeys, 283 million. Litter associated with broiler production, manure generated by laying operations and dead birds are the three primary wastes from the poultry industry. Approximately 12.7 million Mg (14 million tons) of litter and manure were produced on poultry farms in 1990. Broiler litter, a mixture of ma-

nure, bedding material, wasted feed, feathers and soil picked up during recover, accounted for 68% of the total fecal wastes in 1990. Annually approximately 300,000 tons of dead birds require disposal through burial, incineration, rendering or co-composting with poultry litter. About 90% of the poultry wastes are applied to agricultural land. Non-point source pollution of surface and ground water with N, P and pathogenic microorganisms is becoming a major problem in states where the poultry industry is undergoing rapid and concentrated growth.

Production of pork is a major agricultural enterprise in the U.S. The inventory of hogs and pigs tends to fluctuate between 50-70 million on a 4-7 year cycle. The North Central region of the U.S. is the major swine production area with Iowa accounting for about 25% of total production. Swine produce about 14.5 million Mg (16 million tons) of solid waste annually. Approximately 80% of the manure generated can be collected, stored and spread on agricultural land. The major environmental concerns associated with storage or land application of swine manure are surface and ground water quality, gaseous emissions and odors.

The animal manure generated annually in the U.S. contains about 7.5 million Mg (8.3 million tons) of N and 2.3 million Mg (2.5 million tons) of P. By way of comparison about 9.1 million Mg (10 million tons) of N and 1.6 million Mg (1.8 million tons) of P are applied through commercial fertilizers annually. Roughly half the manure is produced in confinement and is recoverable. The efficient conservation and utilization of nutrients contained in animal manures could greatly reduce the need for purchased fertilizers and protect environmental quality. Animal manures are widely variable in chemical composition, physical properties and moisture content. The macronutrient content of manure varies with animal species, type of diet, growth stage and level of performance of the animal, production system employed, amount of bedding material with the manure, and method of manure storage and handling. Average NPK contents in beef feedlot manure are 1.9%, 0.65% and 2.0%, respectively. Macronutrient levels in swine manure vary with the method of handling and storage, but in general are lower than cattle manure

with average values of 0.4% N, 0.1% P and 0.3% K. Poultry manure, with its relatively low moisture content and high macronutrient content (4.6% N, 2.1% P, 2.1% K), is generally considered to be the most valuable animal-manure for fertilizer purposes.

In 1990 there were approximately 133.6 million hectares (330 million acres) of cropland and 263 million hectares (650 million acres) of pasture and range land in the U.S. Nationally this provides an ample base for land application of animal manures. However, economic and environmental considerations place restrictions on the use of some land areas. In some situations enough suitable land does not exist near the site of production to safely accommodate the amount of manure produced. If the manure has to be transported a significant distance from the site of production, transportation costs exceed the fertilizer value of the manure. Available farmland for application of manure generally exists in close proximity to most beef feedlot operations while many poultry production facilities exist in areas with limited capacity for waste utilization. Overcoming economic restrictions associated with transportation costs is one of the major obstacles to more efficient utilization of poultry manure.

Animal manures have traditionally been used as a source of nutrients for crop production. They are applied in solid, semisolid and liquid forms and supply N, P, K as well as secondary nutrients and micronutrients. Many examples of increased crop yields with addition of manures have been documented. Application of manure also improves soil physical characteristics. Organic components of manure can build soil organic matter reserves resulting in increased soil water-holding capacity, water infiltration rates and structural stability. These changes can reduce soil loss by wind and water erosion. Soil application of manure also decreases the energy needed for tillage and reduces impedance to seedling emergence and root penetration. Manures can also be used as an organic mulch when the previous crop does not produce sufficient crop residues to protect the soil surface. Manures stimulate the growth of beneficial soil microbial populations and microbial activity within the soil. Manure application also increases

populations of soil mesofauna such as earthworms that develop channels in the soil that result in rapid passage of water and oxygen to the root zone.

Although the great majority of animal manure is directly applied to agricultural land other uses have been found. Manure can be used for animal refeeding, composting and methane generation. Manures with high crude protein levels can be used in animal refeeding. Approximately 4.2% of the poultry litter produced in the U.S. is mixed with feed grains and fed to cattle. High quality poultry litter is three times more valuable as a feed than as a fertilizer source. The presence of high levels of Cu, other potentially toxic trace elements, drug residues, and parasites in manure and economic considerations place restrictions on refeeding of many manure sources. Energy-efficient equipment to dry and process animal wastes into feed components is needed. Manures have also been successfully used as feed for fish in aquaculture enterprises. Various animal manures have been composted to produce an odorless, fine textured material that has been sold in nurseries and garden stores as a fertilizer and soil amendment. Biogas generation from animal manure has received considerable attention. Methane production from manure has been shown to be an easily established fermentation process, but the total amount of manure utilized for this purpose is still relatively small. The development of methods to more rapidly and completely convert carbon from ligno-cellulose into methane would enhance methane production systems.

Environmental quality must be considered in developing agronomic management practices to effectively utilize animal manures. Manure handling and storage at the production site, and method and rate of application in the field, need to be evaluated in terms of impact on soil, water and air quality. The size of confined animal production units for beef cattle, dairy cattle, swine and poultry continues to increase. These animal production facilities produce huge amounts of animal manure, creating a major disposal problem and causing potential environmental pollution at the production site.

Leaching and runoff of nutrients from manures at the production site and after land appli-

cation can be detrimental to the quality of ground and surface water. Leaching of nitrate-N from animal manures to ground water is a primary health concern. The USEPA has placed a limit on nitrate levels in drinking water at 10 mg N L^{-1} . Nitrate levels in excess of this limit have been found in many water wells in areas with high animal manure production and use. Runoff from production sites and fields receiving manure can pollute surface waters with nutrients, microorganisms, organic materials and soil sediments.

Phosphorus is the nutrient of primary concern from a surface water standpoint, since it is generally considered to be the limiting factor for eutrophication. Phosphorus can be transported in soluble forms or associated with soil or manure particulates. Water-borne pathogens in animal manures can be transmitted to other animals or to humans. Bacterial infections associated with organisms such as *Salmonella*, *Chlamydia* and *Mycoplasma* as well as fungal and protozoan infections have been caused by manure contamination of surface water. Methods to control runoff and erosion will enable us to limit movement of nutrients, organics, pathogens and sediments to surface waters. Methods of surface water control such as terracing, check dams, porous dams, settling basins, tiled infiltration beds, lagoons and vegetative filters have been developed at feedlots to reduce or collect the runoff. Constructed wetlands have also been employed to remove solids and some soluble nutrients before runoff water is impounded in a shallow basin.

Air quality has become a major environmental concern of the animal production industry. Odors are the most frequent source of complaints received by state and federal environmental regulatory agencies against animal producers. Uncontrolled decomposition of manure produces odorous gases including amines, amides, mercaptans, sulfides and disulfides. Ammonia volatilization from manure is an odor problem and contributes to acid rain. These noxious gases can be an irritant to livestock and humans and can cause animal respiratory diseases. Greenhouse effect gases such as CO_2 , CH_4 and N_2O are released from manure storage facilities. Production and accumulation of gases in confined animal areas can be reduced by frequent manure removal, avoid-

ance of overfilling storage tanks, avoiding long storage periods for manure and providing adequate ventilation. Often, however, manures have to be stored for extended periods at the production site because fields are too wet, contain crops or are otherwise not suitable for environmentally safe land application at many times of the year. Application of manures to frozen ground or to wet soils greatly increases the chance for surface water pollution through runoff.

Nutrient conservation is the first step in the development of best management practices for effective manure utilization in agriculture. Nitrogen is the nutrient most susceptible to loss after manure excretion and during storage, transport and land application. Up to 50% or more of the N in fresh livestock manure may be in ammonium form or in a form that can be readily converted to ammonium. At high pHs significant losses of N from manure occur through ammonia volatilization. Even if ammonium undergoes nitrification to nitrites and nitrates it is still subject to losses by leaching and runoff and through conversion to gaseous nitrogen or nitrous oxides under oxygen deficient conditions (denitrification). Under present beef cattle feedlot management practices about 50% of the N excreted in manure is lost before the manure is removed from the feedlot. Another 25% of the N may be lost during transport and application of manure to agricultural land. Thus only about 25% of the N originally present in the manure is available for crop production. Substantial N losses also occur after excretion and during handling, storage, transport and application of dairy, swine and poultry manure. Consequently, considerable research is needed to develop manure management practices that will reduce these losses of N to the environment. Some practices that may have potential for reducing N losses include frequent cleaning; use of carbonaceous bedding materials such as straw, cornstalks, or paper that will create a high C/N ratio thus increasing immobilization of N; use of nitrification and urease inhibitors; and addition of materials to acidify, stabilize or precipitate nutrients in the manure.

Manure needs to be applied to agricultural land at rates that will supply crop nutrient needs, but not adversely affect the environ-

ment. However, suitable methodology for making rapid and economically acceptable field determinations of the nutrient content of manure is lacking. Dependable and practical equipment to accurately spread manure on soils is also a limitation. More information is needed about the basic soil microbiology associated with manure decomposition across a range of soil and climate conditions to accurately predict availability and release rate of major secondary and micronutrients from manure.

Historically, land application of animal manures have been based on the N needs of the crop and a desire to minimize nitrate leaching to ground water. In the case of poultry manure this approach has led to an accumulation of soil P in excess of that required for crop needs. A manure application approach based on P requirement may mitigate the buildup of soil P and lower the risk of nitrate leaching to ground water. However, a soil test P based strategy would eliminate much of the land with a history of continual manure applications from receiving further treatments. Suitable land for safe and economical disposal of poultry manure is already a major problem in many areas of the U.S. In the major poultry producing states, the amount of nutrients produced in manure exceed crop requirements. Economic restrictions on manure transport may result in application of manure to areas with elevated soil N and P contents from previous applications or with high runoff or leaching potentials.

Incorporation of manure into the soil has been a long-term practice to reduce nutrient volatilization, runoff losses and odor problems. Currently many Soil Conservation Service conservation plans significantly restrict or stop fall tillage practices as a means of maximizing residue cover. Therefore, manure incorporation in the fall would constitute a violation of the SCS plan and could result in reduced government subsidy payments. In addition, there are many benefits associated with having a mulch of animal manure on the soil surface including reduced soil erosion. Research is needed to determine cost effective methods of applying animal wastes to the soil surface while avoiding odor problems and volatilization loss of nutrients. Surface application of manure should be compared to incorporation

with respect to disease transmission, pest control problems and potential for runoff and contamination of surface waters.

Best management practices are needed to effectively utilize animal manures for enhanced crop production while avoiding environmental degradation. An integrated resource management systems analysis approach will need to be used to evaluate alternative animal waste management systems. This computer modeling approach which integrates all components of the farm operation will allow different waste management options to be judged based on economic as well as environmental considerations. This approach should identify areas where research is needed and help farmers and planners make waste management decisions.

E. Research Needs

Investment in research and education will be needed to increase and improve agricultural utilization of municipal, industrial and animal wastes. Additional research in the following areas will be needed to ensure efficient and environmentally safe utilization of a variety of readily available waste materials.

1. A national data base listing the amounts produced and the agronomic characteristics of major municipal, industrial and animal wastes is needed.

Future planning to enhance agricultural utilization of waste materials will require a detailed knowledge of amounts produced, geographic distribution of production, and the physical and chemical properties of each material. This will be a difficult task since physical and chemical characteristics of a given waste material can change with conditions of production and method of storage and handling. A range of values for agronomically important parameters such as pH, nutrients, and toxic trace elements, and how these values change with method of production, will need to be known for each major waste source. This agriculturally oriented data base will facilitate selection of waste materials that will benefit the soil/plant system and allow identification of materials with toxic trace element levels that should be restricted in their application to soils.

2. Additional research is needed to develop methods to minimize loss of nutrients from animal wastes during storage, handling and field application.

Up to 75% of the N in manure is currently being lost through ammonia volatilization, denitrification and leaching at the site of production and during transport and application. Often manures have to be stored for extended periods at the site of production until field conditions are appropriate for land application. Large N losses can occur during storage through anaerobic decomposition or during aerobic composting. When applied in the field manures are frequently incorporated to reduce volatile loss of N and odors. However, immediate burial of manures in the soil can result in rapid decomposition, creating anaerobic zones where residual and applied nitrates are denitrified. In addition a large buildup of microbial populations may result in oxidation of as much C out of the soil as was applied with the manure. Incorporation of manures may not conserve N for crop use and could lead to erosion problems by not maintaining a cover of crop residues and manure on the soil surface. New methods are needed to stabilize manures so they can be stored without excessive N loss and odors, then surface applied when conditions in the field are favorable. Research will have to be conducted to evaluate methods of manure stabilization. Coal combustion by-products may be useful for drying and stabilizing animal wastes. The efficiency of crop utilization of N from surface applied and incorporated, unstabilized and stabilized animal wastes will have to be evaluated. Stabilization of manures would reduce N losses thus making more N available for crop needs, reduce odor problems, facilitate storage of manures until field conditions are favorable for application, and make manure applications compatible with erosion controlling no-till systems.

3. Methods are needed to determine the available nutrient content of various wastes to establish acceptable application rates to meet crop needs and to protect environmental quality.

Waste materials need to be applied to agricultural land at rates that will supply crop nutri-

ent needs but not adversely affect the environment. Historically, land application rates of animal manures have been based on N needs of the crop and a desire to minimize nitrate leaching to ground water. However, suitable methodology for making rapid and economically acceptable field determinations of the nutrient content of manure is not available. In addition basic research is needed on the microbiology of manure decomposition in soil to accurately predict availability and release rate of nutrients. Testing protocols are needed to assess the potential mineralization of organic N in municipal wastes to allow more efficient N management. Municipal wastes will frequently need to be spiked with N fertilizers to supply crop N needs. In the case of poultry manure, application rates may need to be based on P rather than N, since soils with a history of poultry manure application tend to have excess P levels. The development of effective methods to estimate plant available nutrient levels in wastes will allow selection of application rates that will satisfy plant nutrient requirements while minimizing environmental risks.

4. Research is needed to develop improved methods to reduce contamination of surface and ground water by nutrients and pathogenic microorganisms from animal and municipal wastes.

Contamination of surface and ground water with N, P and pathogenic microorganisms can diminish water quality and pose human health risks. Elevated nitrate levels in drinking water is a primary health concern. Nitrate levels in excess of the USEPA limit have been found in water wells in areas with high annual manure production and use. Part of this problem may be solved by improved manure handling at the production site. More needs to be known about N dynamics and leaching in soils. Models to describe and predict the fate of N in soils would allow identification of areas where nitrate leaching will be a problem and special management practices will be required. Improved management techniques to reduce nitrate leaching to ground water are needed. Phosphorus contamination can lead to eutrophication of surface bodies of water. Excess soil P, resulting from land application of poultry manures, poses a risk to sur-

face water quality in many areas. Research should be directed toward defining acceptable upper limits for available soil P resulting from repeated manure applications. Critical soil test P levels which lead to eutrophication of sensitive water bodies should be identified. A need exists for a soil test which relates P levels in the soil to P runoff from fields. Water-borne pathogens in animal manures can be transmitted to other animals or to humans. Human health problems resulting from contamination of drinking water supplies by pathogenic microorganisms from animal wastes are frequently reported. Improved waste management practices at the production site and control of erosion and runoff in the field will greatly reduce pathogen movement to surface waters. The development of techniques to reduce N, P and pathogenic microorganism movement to surface and ground water will result in improved water quality and limit risks to human health.

5. An assessment of the risks associated with trace elements and synthetic organics in municipal and industrial wastes must be made to allow development of appropriate regulations for land application of these materials.

Many of the new industrial by-products and municipal solid waste compost have variable levels of trace elements and synthetic organic compounds. A careful assessment of the risks associated with land application of these materials should be performed in the field using sustainable agricultural techniques. The fate and effects of trace elements and synthetic organic chemicals on soils, plants, animals and humans must be determined. A risk assessment pathway approach similar to that used to develop regulations for land application of sewage sludge will be needed for other municipal wastes and industrial wastes. Using this approach the USEPA was able to establish regulations for levels of trace elements and synthetic organics in sewage sludge and to determine cumulative amounts of these components that could be land applied. This risk assessment information concerning municipal and industrial wastes will be needed to address public concerns about adverse impacts associated with the use of these materials and to convince the agricultural community that it is in

their best interest to utilize these materials. The specific information gained in these investigations can be used as the basis for developing regulations for land application of municipal and industrial wastes.

6. Research is needed to determine the chemical behavior of coal combustion by-products in soil.

A variety of new coal combustion by-products are being produced by fluidized bed combustion (FBC) techniques and flue gas desulfurization (FGD) processes. Mineralogical and chemical changes occurring when these by-products are added to soil greatly influence the environment for plant growth. Many of the FGD by-products contain appreciable amounts of calcium sulfite. Calcium sulfite is difficult to dewater, has a lower solubility than calcium sulfate and may inhibit plant growth when added to soil. While calcium sulfite can be oxidized to calcium sulfate at the power plant at a cost of about \$4.40 per Mg (\$4 per ton), oxidation in soil would be preferable. Research is needed to determine favorable conditions for rapid oxidation of sulfite to sulfate in soils. This information would allow soil conversion of potentially toxic sulfites to calcium sulfate which is beneficial to crops.

7. Research is needed to develop methods to enhance soil organic matter levels through large additions of organic wastes without causing environmental problems.

Many of our soils have lost organic matter through erosion of topsoil and tillage accelerated biological oxidation. Soil organic matter is essential for favorable soil physical properties, soil-plant-water relationships, microbial activity and nutrient cycling. Organic matter in the form of sewage sludges, municipal solid wastes and animal manures is available for use in some of these soils, but in many states current laws limit applications of these wastes to no more than amounts needed to supply crop nitrogen needs for one to three years. The laws were developed to prevent contamination of water supplies, but they also prohibit using application levels of organic wastes high enough to build soil organic matter to desired levels. Currently techniques are not available to apply sufficient amounts of organic wastes

to substantially increase soil organic matter without causing potential ground water contamination from N in the waste. Research is needed to find ways to add needed carbon and nutrients from wastes into the biomass and residual organic matter of soils and into crop production without releasing undesirable levels of N into the air and water. Possible approaches to this problem could include: keeping the wastes on the soil surface where they would dry and decompose more slowly, use of nitrification inhibitors, and use of cover crops, crop rotations or intercropping to intercept nitrates. Benefits associated with enhanced soil organic matter levels would include: protection from erosion, increased water infiltration rates, higher available water holding capacity, increased rooting depth and enhanced supply of nutrients. The ability to apply higher application rates of organic wastes could reduce transportation and application costs to waste producers.

8. Methods need to be developed to produce composted municipal solid waste and sewage sludge suitable for use in the horticultural industry.

Containerized plant production accounts for a \$4.7 billion segment of the horticultural industry. Peat, milled pine bark or shredded hardwood currently supply the organic material typically found in containerized growth media. At least 40% of this organic fraction could be supplied by other sources including composted municipal solid waste and sewage sludge. Quality and maturity criteria would need to be developed so composted municipal waste with a dependable standard of quality in terms of pH, soluble salts, nutrient content and particle size could be produced. Compost specialty products could also benefit the horticultural industry. Composts made from a variety of organic materials have the potential to control plant diseases caused by soilborne pathogens such as *Phytophthora*, *Pythium*, *Rhizoctonia*, and *Sclerotinia*. Methods need to be developed to dependably enhance the microbially-mediated plant disease suppressive characteristics of compost. This would significantly lessen the need for biocides in the horticultural industry. Methods need to be developed to reliably inoculate horticultural grade composts with beneficial rhizosphere mi-

crobes that can biologically mediate nutrient uptake by plants thereby reducing the dependence on synthetic fertilizers.

9. Research is needed to blend, mix or co-compost different wastes to produce a final product with desirable characteristics for agricultural or horticultural uses.

The safe and beneficial utilization of waste materials in agriculture and horticulture will depend on the development of products with a known and consistent range of physical and chemical characteristics. In some cases it may only take a simple change in a waste material to generate a more valuable product. The value of municipal wastes as biofertilizers can be enhanced by addition of fertilizers. Segregation of an input component with high levels of toxic trace elements or hazardous organic chemicals will make the resulting solid waste compost a more safe and useful product. Often it may be necessary to blend, mix or co-compost various waste materials to get a final product with desirable characteristics. Research is needed to determine methods to reduce the plant availability of toxic trace elements in waste materials. Examples of this type of research include: (1) addition of waste iron and manganese oxides to sewage sludge or sludge contaminated soils to reduce Cd availability, and (2) mixing fly ash with sewage sludge. Research is needed to develop process technology to co-compost sewage sludges and biodegradable fractions of municipal solid waste to enhance product quality and acceptability. Additional research is needed to investigate the possibility of stabilizing animal manures from nutrient loss by blending with coal combustion wastes. Research would need to be conducted to assess the benefits/risks associated with these and other waste mixtures. This research could result in "designer wastes" with beneficial characteristics for agricultural and horticultural uses. Although the waste producer will have to spend additional money to generate a more useful product, the cost may still be less than the currently available disposal alternatives.

10. Regulations that protect the environment and human health while allowing utilization of beneficial materials must be developed and uniformly applied by regula-

tory agencies to increase agricultural utilization of wastes.

Environmental regulations developed and interpreted by individual states currently constitute one of the main barriers to increased agricultural utilization of wastes. In some instances these regulations may not have a sound scientific basis. A strong and understandable desire to prevent pollution may result in excessively restrictive legislation. This may take the form of zero impact legislation that will not allow application of waste materials if they increase soil concentrations of certain trace elements even if there is no measurable environmental or human health risk. Regulators have a strong incentive to avoid taking risks and therefore they do not look for innovative and beneficial ways to handle wastes. Waste producers are frequently hesitant to apply wastes to land since they fear that laws may change and they may have the legal responsibility to clean up a site treated with a previously allowed material. The development of regulations that control addition of nutrients, trace elements and organics in wastes based on a risk assessment approach coupled with uniform interpretation of the regulations from state to state will create a more favorable situation for agricultural utilization of beneficial wastes.

11. Efforts are needed to educate the agricultural community and inform the public about advantages associated with agricultural utilization of wastes.

Successful handling of the waste disposal problem will require a partnership between the urban and agricultural sectors. The agricultural sector will need to know which waste materials can be land applied, how much can be applied and what are environmentally safe methods of application. Education/extension bulletins and computer packages which assist the farmer in developing waste utilization plans will be needed. The public will need to be convinced that agricultural utilization of wastes is environmentally safe, cost effective and does not pose a human health risk. Farmers may have to be subsidized to help the public solve the waste disposal problem. This may take the form of subsidies to pay transportation costs to haul waste materials to suitable

sites for land application. Waste producers and the public may have to pay additional fees to convert wastes to forms with greater value for agricultural and horticultural uses. However, these expenditures may be small compared to increasing costs of current waste management practices and the benefits to be gained through environmentally safe utilization of wastes in agricultural operations.



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